MOBILE MUSIC TOUCH: USING HAPTIC STIMULATION FOR PASSIVE REHABILITATION AND LEARNING

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Tanya Thais Markow

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MOBILE MUSIC TOUCH: USING HAPTIC STIMULATION FOR PASSIVE REHABILITATION AND LEARNING

Approved by:

Professor Gregory Abowd,
Committee Chair
College of Computing
Georgia Institute of Technology

Professor Thad Starner, Advisor
College of Computing
Georgia Institute of Technology

Professor Melody Moore-Jackson
College of Computing
Georgia Institute of Technology

Professor Ellen Yi-Luen Do
College of Computing
Georgia Institute of Technology

Professor Deborah Backus
Crawford Research Institute
Shepherd Center

Date Approved: May 2012

To my daughter,

Morgan Brittany Markow,

You inspire me. I love you.

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“Ad Astra Per Aspera” - A Rough Road Leads to the Stars

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SUMMARY

Hand rehabilitation after injury or illness may allow a patient to regain full or at least partial use of a limb. However, rehabilitation often requires the patient to perform multiple repetitions of motions. While absolutely essential to regaining usage, such exercises are not always mentally engaging or enjoyable for the patient. The loss or degradation of the use of the hands can cause considerable loss of independence.

In this dissertation, we present Mobile Music Touch (MMT), a wireless glove paired with a computing device, such as a laptop, smart phone, or MP3 player. The MMT system plays a song, while also "tapping" the fingers using vibration motors to indicate the correct finger to use to play the song on a piano keyboard. Learning a new skill or activity without active focus, an idea called Passive Haptic Learning (PHL) may allow an individual to learn one skill through their sense of touch while performing another, unrelated activity. Most rehabilitation activities are active in nature, requiring the focused participation of the injured person. Passive rehabilitation is the idea that some technologies and activities may bring about beneficial changes without the active engagement of the injured person. In order to study the concepts of PHL and PHR, we propose the Mobile Music Touch (MMT) system. We show that using passive rehabilitation in conjunction with the active rehabilitation of piano playing will bring about a greater degree of improvement in the hands than that achieved using only active rehabilitation.

This dissertation research makes three unique contributions. First, we demonstrate that Passive Haptic Learning (PHL) using just the sense of touch is feasible and provides a form of learning and reinforcement of learned skills and tasks. Second, we identify the attributes and design features of a glove suited for long term wear

by persons who use a manual wheelchair for mobility. Third, we show that Passive Haptic Rehabilitation (PHR) is possible using vibrotactile stimulation of the hands in persons classified as tetraplegic due to incomplete spinal cord injury.

CHAPTER I

INTRODUCTION

1.1 Mobile Music Touch (MMT)

Rehabilitation after suffering injury or illness may allow a patient to regain usage of a disabled limb. However, rehabilitation often requires the patient to perform multiple repetitions of motions. While absolutely essential to regain usage, such exercises are not always mentally engaging and enjoyable for the patient. The loss or degradation of the use of the hands can cause considerable loss of independence. The hands are essential to communication through writing and typing and, even more basically, the ability to feed and care for oneself. An engaging and fun form of hand rehabilitation may help encourage the patient to perform rehabilitation exercises more often. If such rehabilitation also allows the patient to learn a new skill, such as playing the piano, the patient may even continue to engage in the rehabilitative exercise for life. However, most adults do not have the time to devote to learning a new skill or activity, as learning usually requires the active and often undivided attention of the learner. Learning a new skill or activity without active focus, an idea called Passive Haptic Learning (PHL), may allow an individual to learn one skill through their sense of touch while performing another, unrelated activity. Most rehabilitation activities are active in nature, requiring the focused participation of the injured person. Passive rehabilitation is the idea that some technologies and activities may bring about beneficial changes without the active engagement of the injured person. Several studies have shown some possible rehabilitative benefits from haptics to bring about improvements in persons with injuries involving the central nervous system. One possibility is that the ability to complete motor activities correctly requires feedback from the afferents in the peripheral nervous system [28]. The afferents are the nerves that take signals from the sensory organs, of which the skin is the largest in the body, and return those signals back to the brain for processing [49]. Haptic stimulation of those afferent nerves using vibration motors, for example, may help improve fine motor control of the hands due to improvements in the ability to sense or feel with the hands. We have dubbed the concept of providing rehabilitation while the recipient is engaging in an unrelated activity Passive Haptic Rehabilitation (PHR). In order to study the concepts of PHL and PHR, we developed the Mobile Music Touch (MMT) system, which we discuss in greater detail in Chapter 3.

Thesis Statement: The use of passive rehabilitation in conjunction with the active rehabilitation of piano playing will bring about a greater degree of improvement in the hands than that achieved using only active rehabilitation.

The studies we conducted to examine this thesis have led to several contributions to the field.

- First, we demonstrate that Passive Haptic Learning using the sense of touch is feasible and provides a form of learning and reinforcement of learned skills and tasks.

- Second, we identify the attributes and design features of a wearable PHL system that is best suited for long-term wear by persons who use a manual wheelchair for mobility.

- Third, we demonstrate the extent to which Passive Haptic Rehabilitation may provide an engaging and effective form of rehabilitation using vibrotactile stimulation of the hands in persons classified as tetraplegic due to incomplete spinal cord injury. A Passive Haptic Rehabilitation method may provide a relatively inexpensive way to allow persons with spinal cord injury to continue to practice rehabilitative activities long after the first year post-injury. A low-cost alternative that improves quality of life and increases independence for the patient may at some point be covered by insurance, as greater independence of a person with SCI reduces total cost for life-long caregivers and long-term care facilities.

In Chapter 2, we review related work, and Chapter 3 covers detailsabout the Mobile Music Touch (MMT) system. Chapter 4 reviews studies conducted to determine the effectiveness of Passive Haptic Learning. Chapter 5 discusses features of glove design for persons using manual wheelchairs. Chapter 6 covers studies conducted on Passive Haptic Rehabilitation. Chapter 7 consists of discussions and future work, and we finish with conclusions in Chapter 8.

CHAPTER II

BACKGROUND AND RELATED WORK

2.1 Passive Learning

Playing music requires fine dexterous motion of the hands, something of great importance to persons undergoing hand rehabilitation. Playing music also provides a mentally challenging outlet, distinguishing itself from other, more repetitive forms of hand rehab. However, as with all such skills, practice is required to reinforce what has been learned and maintain an achieved level of proficiency. Unless a newly-learned song is rehearsed, the musician will quickly begin to forget the passages [27]. We consider here not only active learning, when a person is actively engaged in the task being learned, but passive learning. The phrase that learning is "caught, rather than taught," well defines passive learning. In other words, the student may be focusing on an activity but manages to learn a skill that is unrelated to the task on which she is actively focused [58].

2.2 Haptic Wearable Interfaces

The sense of touch offers an alternative to video and audio for communicating information to a user with a wearable device [90]. Vibration is already used in smart phones to provide a more discreet way of alerting the user to an incoming call, text or email. However, it may be possible to exploit vibration to convey more refined information, such as who is calling or the subject of a particular message based on vibrational patterns [64, 63]. The use of the sense of touch in this regard is especially attractive considering the abilities of humans to perceive and process signals using our senses [19]. While most people like to think they have become experts at multi-tasking, stories of accidents that may have been caused by texting [22, 54] and studies in the areas of texting and driving have demonstrated that users' perceptions of multi-tasking expertise to be false. Drews et al. found that participants who texted while driving in a simulator (dual-task condition) had a significant increase in braking and following distance versus just driving in the simulator (single-task condition). It was thought by the researchers that the increased following distance may be an active attempt to avoid an accident, as subjects realized the distraction of texting. Dual-task participants also displayed a noted increase in lane crossings, lane reversals, and gross lateral displacement over single-task condition participants [36]. Vibrotactile wearable devices may allow users to interact more with others without the undue distraction that is demanded of visual or auditory stimuli. One concern in this area is how well humans can distinguish information delivered via vibrotactile methods. "Change blindness" describes the phenomenon of not being able to detect changes in visual scenes [84]. Gallace et al. demonstrated the concept of "change blindness" applies to the sense of touch as it does in vision [41]. The researchers conducted an experiment in which vibration tactors were placed in several locations on the participant using Velcro over his or her clothing. Participants were asked to determine if there was a perceptual difference in the vibration patterns sequentially presented. Gallace et al. found that if a "mask" was placed between two vibrational patterns (mask being defined here as vibrating all the tactors at once), the participants were less likely to detect changes in the vibration patterns just prior to and after the mask being administered.

2.3 Haptics and Learning

Haptics may not only provide another medium for conveying information, but it may also be used to train a user in a new task or skill through vibrotactile feedback.

Schumacher et al. found in their study that humans are better at multi-tasking when stimuli are being received by different senses (auditory and visual) [82]. When humans are presented with multiple stimuli on a single channel, for instance two visual stimuli at the same time, they tend to prioritize one task over the other [80]. These findings suggest that humans are able to process large quantities of sensory information, so long as it is coming from different sensory systems. How much of this massive amount of incoming data from our senses is actually processed and used? How do sensory inputs become learned skills? A model for learning and memory was proposed in 1968 by R.C. Atkinson and R.M. Shiffrin in their paper "Human Memory: A Proposed System and Its Control Processes." They postulate three major components of human memory, "the sensory register, the short-term store, and the long-term store" [13]. The sensory register is considered to be large but exceedingly brief in nature. Inputs to the sensory register persist for an estimated one quarter to two seconds before being lost. Some degree of attention must be paid to the sensory input in order to commit it to short-term store (STS), where it may generally persist for 5-20 seconds. In order to commit information to long-term store (LTS), practice or rehearsal is necessary [13, 29]. Several studies have explored the processing of visual and auditory stimuli. Molholm et al. demonstrated that multisensory stimuli (specifically here auditory-visual or AV) are processed differently than that for unisensory stimuli (either auditory or visual sensory input, presented independently). The two types of stimuli map to different topographies in the brain. They found that the reaction time of a participant was faster for multisensory stimuli (AV) than for that of unisensory stimuli [73]. Going beyond visual and auditory stimuli, we must explore the sense of touch as another possible form of input that may be integrated into the learning experience [42].

The possibilities for training using vibrotactile feedback range from learning to play a musical instrument to dancing. Over several studies, van der Linden et al. explored the use of vibrotactile feedback to aid in teaching students to play the violin properly [93, 94]. Their device, the MusicJacket, is fitted with several vibration motors which cue the user in two particular violin skills: holding the violin properly and straight bowing. For bowing, the instructor calibrates the jacket by physically guiding the student through a correct motion. After calibration, when the student plays, the vibration motors fire if the wearer deviates from the ideal path, serving as a non-verbal reminder of the correct path. The same technique is used to aid the student in keeping the violin in the proper position. Again, if the student deviates from the ideal position (they usually allow it to fall slightly), the vibration motors fire. The MusicJacket has five vibration motors. Three are on the arms to serve as a push or pull reminder to ensure proper bowing motion; they are located on the bowing arm behind the elbow, on the wrist and behind the elbow. Two vibration motors are located on the ribs, to serve as a reminder to lift the violin if it settles too low over time. The authors found that the MusicJacket helped students hold the violin properly, execute straight bowing and use the correct amount of bow. These improvements were directly related to the students' need (i.e., more advanced students did not benefit as much from the cueing to hold the violin properly, but novice students did see benefits in this area) [96]. In another study, van der Linden et al. demonstrated that using the MusicJacket provided improvements in violin playing over that of a control condition [95]. They were careful to consider qualitative feedback in a small study with a prototype of the MusicJacket, finding that the users must learn to understand and interpret the vibrotactile signals in order to get the most benefit from them [56].

Drobny et al. proposed a system which provides augmented feedback, specifically video, audio and tactile, to train people to perform dance sequences. The system was an expansion of an earlier concept designated Saltate! which used acoustic feedback to help a couple to perform a slow waltz to the correct timing and beat [38]. However, they found that users still had difficulty in learning choreography. Expanding on the idea proposed by Nakamura et al., which used vibrotactile cues to train dancers to make correct arm movements in traditional Japanese folk dance [76], Drobny et al. used vibration motors located on the left, right, front and back of each dancer's ankles [37].

2.4 Innervation of the Hand

The three main nerves leading into the hand are the ulnar, median, and radius. Each of these nerves innervates a different part of the hand cutaneously, depending on the side, palmar or dorsal. As illustrated in Figure 1 [18], on the back or dorsal side of the hand, the radial nerve supplies the entire thumb and the very base of the index and middle fingers.

On the dorsal side, the median nerve supplies the distal portions of the index, middle and half of the ring fingers. Completing the dorsal side innervation, the ulnar nerve supplies half the ring finger and all of the pinky. On the palmar side, the median nerve supplies the thumb, index, middle, and half of the ring finger. Continuing on the palmar side the ulnar nerve supplies half the ring finger and all of the pinky [24].

2.5 Spinal Cord Injury

Spinal Cord Injury (SCI) may be due to injury or disease and is classified by the level of injury along the spinal column as shown in Figure 2 [6]. Two main classifications are often used as well, complete and incomplete. Complete SCI indicates a lesion that results in no volitional motor function or sensation below the level of injury. Incomplete SCI implies some voluntary movement below the point of injury and some sensation. In the US, there are 7,500 to 10,000 new injuries each year. The predominant group is young men, with a peak age of 19 years. The cervical cord is the most common site of injury (54% of cases), followed by the thoracic (about 36%), and lumbar cord (10%). About 250,000 people in the U.S. are considered spinal cord injured [65]. We specifically wished to work with persons who have SCI

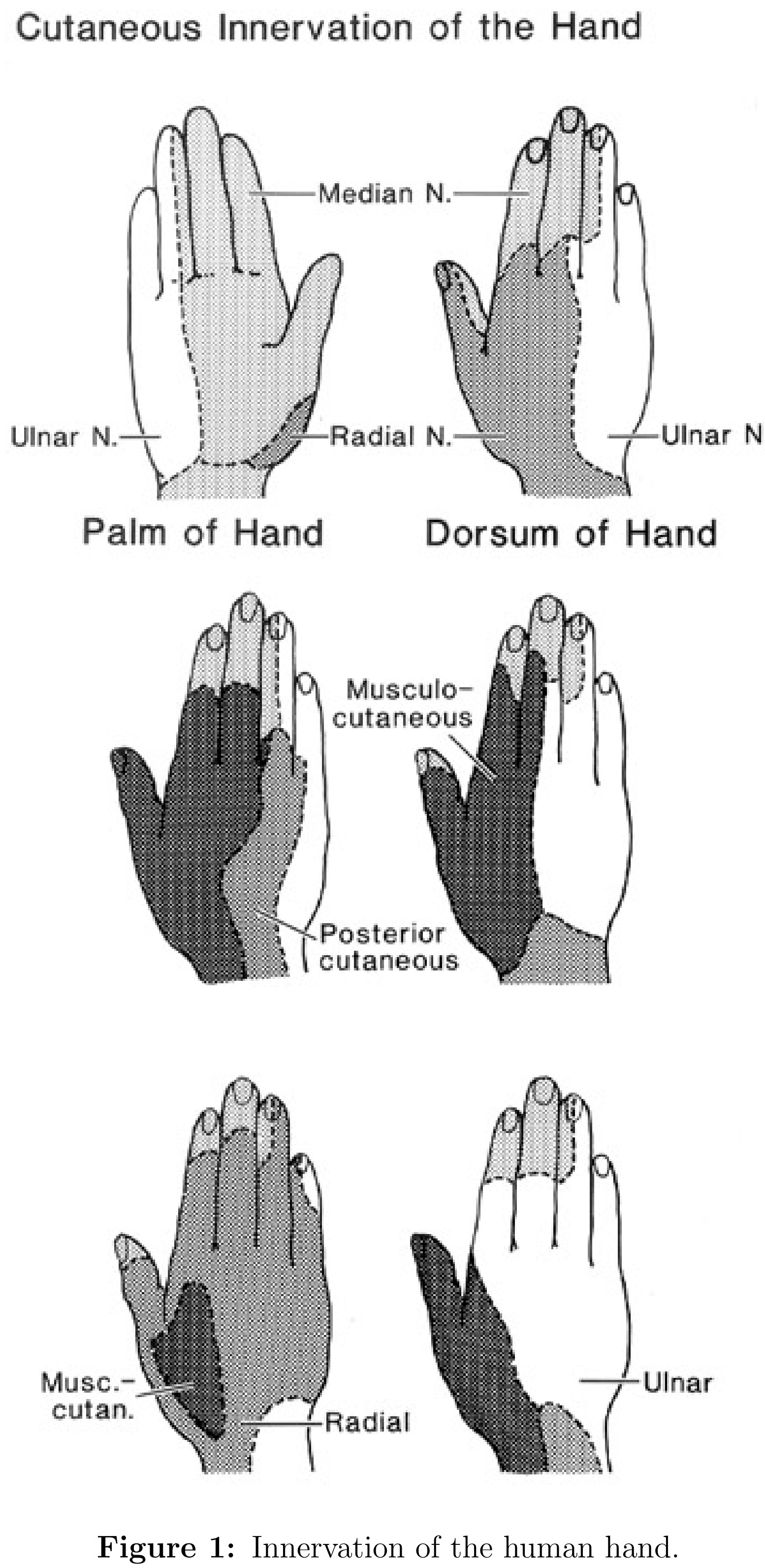


Figure 1: Innervation of the human hand.

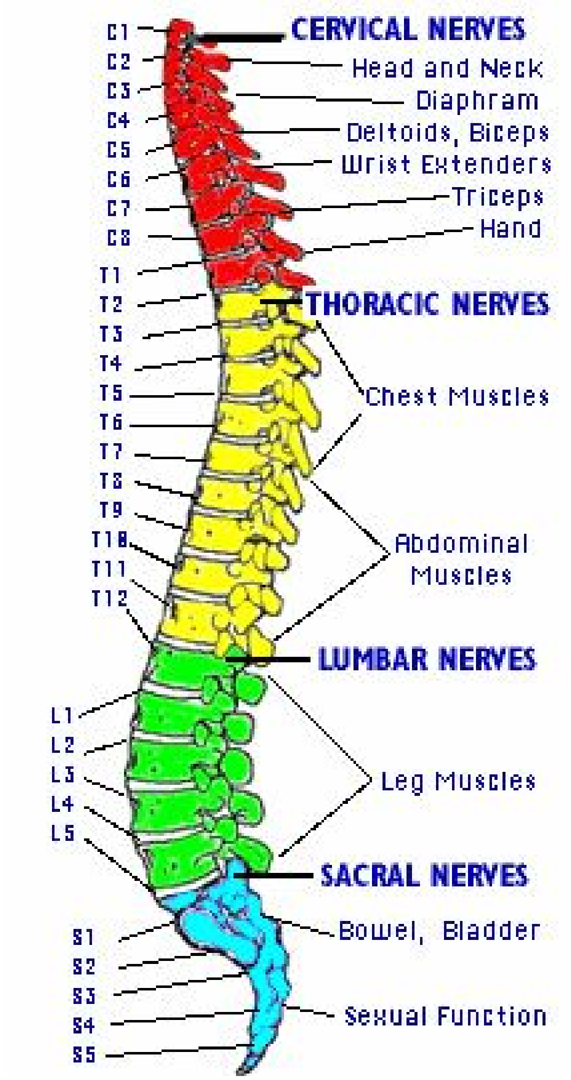


Figure 2: Spinal column with vertebrea levels indicated on the left side of the figure.

with incomplete tetraplegia. Persons with incomplete tetraplegia often have some hand function, but may have reduced sensation and motor function of the fingers and hands.

The American Spinal Injury Association (ASIA) Impairment Scale (AIS) is often used to classify spinal cord injuries [8]. The levels are detailed below:

1. ASIA A Complete; no motor or sensory function preserved in the sacral segments S4-S5.

2. ASIA B Incomplete; sensory but not motor function is preserved below the neurological level and includes the sacral segments S4-S5.

3. ASIA C Incomplete; motor function is preserved below the neurological level and more than half of key muscles below the neurological level have a muscle grade less than 3.

4. ASIA D Incomplete; motor function is preserved below the neurological level and at least half of key muscles below the neurological level have a muscle grade of 3 or more.

5. ASIA E Normal; motor and sensory function are normal.

Muscle grading, mentioned previously in the AIS discussion, further refines a SCI [10, 99]. A five-point scale is often used, specifically:

1. Grade 0 Complete paralysis. No observed function.

2. Grade 1 Trace. There is some observable contraction, but no joint motion.

3. Grade 2 Poor. Gravity is not a factor; full range of motion can be achieved.

4. Grade 3 Fair. Full range of motion at the joint against gravity.

5. Grade 4 Good. Full range of motion is accomplished, even against gravity and in the presence of some resistance.

6. Grade 5 Normal. Full range of motion, against applied resistance and force of gravity.

2.6 Spinal Cord Injury Upper Extremity Rehabilitation

In terms of preference for rehabilitation and possible outcomes, Anderson found that among persons with SCI resulting in tetraplegia, “48.7% of the participants indicated that regaining arm and hand function would most improve their quality of life" [12], the highest ranking of all responses. Anderson's finding supports the need to focus on upper extremity rehabilitation to ensure maximum independence for persons with SCI. Upper extremity abilities dictate the level of independence of a person with SCI and must be maintained. Daily activities that require the upper extremities and are particularly crucial for people with tetraplegia are the ability to transfer from surface to surface (for example, wheelchair to standard chair or bed) [85], hygiene, and feeding. Beyond basic care activities, the upper extremities are key to allowing persons with SCI to communicate via phone and internet and for work and recreation. Current standard clinical practices for persons classified as tetraplegic due to SCI include splinting [30], massed practice [17], tendon transfer surgery [40], and compensation methods using spared muscles. While these therapies are proven and effective, they are not always mentally engaging, and activities like massed practice are often discontinued after leaving the hospital.

2.7 Robotics in Rehabilitation

Rehabilitation necessarily involves repetitive motion for a duration that allows positive changes to occur. Unfortunately, there is not yet widespread recognition that positive changes may still result after the first year post-injury. For the first year after the injury, there is generally a steep improvement, then a tapering-off of improvements. As a result, insurance may cover very little or no significant rehabilitation after this initial period. In addition, the cost of in-patient programs can be prohibitive, and transportation to and from an out-patient program can be difficult. It would be ideal if some forms of rehab might be accomplished in the home setting. Sending a physical therapist to the home, while ideal, would quickly become a huge financial burden. Ensuring patient compliance with at-home programs is difficult. Without motivation and monitoring, even high-tech devices may lie neglected like the proverbial treadmill that becomes a hat rack. Robotics in rehab may offer one solution. Colombo et al. present a novel approach to these issues, developing two robots for upper extremity rehabilitation for persons who have suffered stroke [26]. They identify and address the issues of motivation, customization to a specific set of needs, and ease of use for the therapist and participant. They developed a one degree of freedom (DOF) wrist manipulator and a two DOF elbow-shoulder manipulator robots. They collected quantitative and qualitative data on the use of the robots, testing persons who were in an in-patient status in a clinical environment. They found that making a game-like scenario helped motivate users by keeping score, and they increased the possible range of motion when the user achieved a maximum score. The authors recognized that a motivating, game-like interaction would be of particular benefit, as a therapist is often greatly responsible for the motivation of a person in rehabilitation [53]. The interface was made user-friendly, not only for the participant, but also for the therapist, who is able to customize the exercises for a specific user and monitor progress [26]. One aspect that was particularly attractive about this work was the author's recognition of the key role of a therapist in compliance, motivation, and expertise. A robotic, in-home rehab system allows highly skilled therapists to provide their services to more people while minimizing their need to travel or simply repeat monotonous motions. The robot can do these exercises, while providing the therapist with key information to tailor the rehab to the specific user. While initial cost of such a system may be high, the resulting benefits may allow for greater independence and less care costs over time.

2.8 Haptic Feedback in Rehabilitation

People who have suffered a stroke or have Multiple Sclerosis often experience a loss or reduction of sensory perception of the affected limb(s). In such a case, the individual may lose confidence in the ability to use the disabled limb, leading to a reduction in use of the limb, a phenomena known as “learned disuse” [35]. “Learned disuse” can lead to muscular atrophy, causing further weakening and even more reluctance on the part of the individual to use the limb [33]. Rehabilitation seeks to curtail this downward spiral by empowering the patient to use the limb as often as possible. Jiang et al. proposed an innovative method using haptic feedback, in the form of vibration, as a way to increase confidence in the use of the more affected limb, in this case, an arm and hand [55]. One problem that plagues people with reduced sensation in the hands is not knowing the amount of pressure being applied to objects being handled. For example, if one seeks to pick up a glass and does not apply enough pressure, it is likely to fall out of the hand and break; if too much pressure is applied, one may break the glass with the force applied, possibly causing injury. If the patient could be provided with some way of knowing how much pressure is being applied by the more affected hand, he or she might be more inclined to use the hand to grasp objects, improving confidence in the use of the hand. To accomplish this, Jiang et al. created a set of force sensors, applied to the index, middle, and ring fingers of the more affected hand and a harness for the less affected hand with vibration motors applied to the fingernails of the corresponding fingers. As pressure is applied to an object with the more affected hand, the vibration motors increase their vibration to tell the wearer that they are applying an increasing amount of pressure [55].

The idea of the work above is to provide an alternate form of feedback to the wearer that may replace that lost by illness or injury. This concept is discussed by Doidge at length; specifically he illustrates a case in which a woman lost her ability to balance due to a drug reaction [35]. Doidge describes how Paul Bach-y-Rita essentially replaced the signals normally sent to the brain to maintain balance with a small strip with accelerometers & electrodes placed on her tongue, which provided a feeling akin to small bubbles moving around in response to motion and position. Her brain quickly adapted to this new form of information, and she was able to regain her ability to balance [35].

Many researchers are exploring the use of tactile systems to provide persons who have diminished sense of touch due to injury or disease with a form of artificial feedback. Merrett et al. examined three types of tactile devices, specifically "vibration motors, a motor-driven 'squeezer,' and shape memory alloys" [71]. The writers state that vibration may be used to provide cueing information, a concept we explore with MMT. Vibration has also been used in conjunction with "belts" around fingertips to simulate pressure, as when touching an object. Shape Memory Alloys (SMAs), are metals that are fairly pliable at room temperatures and can "remember" a given shape when pressure is applied. Wires made of SMAs have been explored and used in thimble-like devices worn on the fingers. Lengthening and shortening of the SMA wires wrapped in the thimbles due to changes in temperature increase and relieve pressure on the fingers, providing a sensation of pressure. The researchers developed and iteratively refined through able-bodied user trials three devices to try to simulate pressure when touching a surface. They found that their SMA device was better at simulating the feeling of grasping an item, but that the vibration-based systems were best for simulating the feeling of the surface of an object. Merrett et al. also found that the stimuli of temperature and vibration sensations made it more difficult for their participants to perceive the object they were touching [71].

Kurita et al. explore a different use of vibration application to the hands. The researchers developed a wearable device that provides vibration to the sides of the fingers to provide "white-noise vibration" thereby enhancing the wearer's sense of touch, which may result in improvement of fine motor skills. In this study, the authors investigated "stochastic resonance" by performing three tests of tactile sensitivity and two of motor ability. The participants were evaluated in these areas while wearing the system. The sensorimotor enhancer was placed on the radial side of the fingers to ensure the palmar area was free to be used for touching and handling objects.

Six different amplitudes of vibration were applied, and the full battery of evaluations were performed for each amplitude. The three sensation tests consisted of a two-point discrimination test, a one-point test, and a sandpaper comparison test. The two-point discrimination tests evaluates the participant's smallest perceivable distance between two gently applied sharp points. The one-point test uses monofilaments applied to the fingertip; in this case, the user must simply state whether or not he feels it. The sandpaper test consisted of having the wearer try to determine which randomly selected sandpaper sample out of a possible nine grit sizes he or she felt. The first motor evaluation had the participant attempt to apply a specific percentage of their pre-test measured fingertip force while wearing the device set at various amplitudes. A grasping task evaluated the participant's ability to hold an object weighing 140g for a period of 3 seconds in a pinch grasp, with just enough force to hold the object without dropping it. The amount of force applied was recorded for each trial. The authors found statistically significant improvement in sense of touch for some amplitudes on the two-point discrimination test and the one-point test, but not on the sandpaper test. For the motor tasks, the fingertip force evaluation did not achieve statistical significance for any of the amplitudes, but there was some success for two amplitudes on the grasping test. All of these evaluations were performed on uninjured, healthy participants. [60].

2.9 Electro-Stimulation Rehabilitation

Haptic feedback is defined as using the sense of touch to provide information to the user of a device. A good example of such feedback is a cell phone with a vibration setting that alerts the user of a call without an auditory tone. Haptic feedback has great potential, but we also seek the advantage that vibration may produce in terms of rehabilitation. One area of continued exploration is that of electro-stimulation. Dimitrijevic, Soroker, and Pollo demonstrated the use of electrical stimulation with persons suffering the effects of stroke and Spinal Cord Injury (SCI). They took a unique approach; instead of applying electro-stim to specific points on the limb, they instead explored applying it to the entire hand. To accomplish this task, they had the participant wear a mesh wire glove capable of conducting electricity. To ensure even distribution of the stimulation, they also had users immerse the gloved hand in a conductive jelly. Their work produced several positive results, including a reduction in muscular spasticity, improved sensory perception in the hands, and increased range of motion in the affected upper extremity [34]. These benefits were also observed when the stimulation was below the ability of a human to detect it. Interestingly, the improvements in range of motion, spasticity, and sensation were not observed to decline even when the intervention was stopped for a month [33]. Dimitrijevic continued to explore the use of electrical stimulation applied to the afferents of the hand with Golaszewski, Kremser, Wagner, Felber, and Aichner. This team looked at the brain cortical activity of six uninjured subjects using Functional Magnetic Resonance Imaging (fMRI) performing a 20 minute finger-to-thumb tapping activity. They found that applying whole hand mesh-glove electrical stimulation (below the threshold of perception) resulted in an increase in cortical activity not seen when the sham case (no stimulation) was applied. They measured this effect by analyzing the number of activated pixels on fMRI scans (representing blood flow in the brain) when the activity was performed [43]. This study further reinforced findings from earlier stroke studies using the same mesh-glove stimulation. These studies are interesting because it appears that the electrical stimulation, even below the sensory threshold, seems to have an effect on the somatosensory system and the motor cortex.

Sarabon et al. propose, based on a previous study by Claus et al. [23], that mechanical stimulation of the afferents may benefit hand motor control [81]. Rehabilitation is often tedious and focuses the patient on recovering or compensating for lost abilities. The need for the rehabilitation process itself can be discouraging. Patients sometimes quickly abandoned rehabilitation routines to his or her detriment. Dimitrijevic writes that "diminished afferent input to the brain from the affected hand is a common deficit after stroke. People with SCI may become less aware of their affected upper extremity because of sensory loss and part paralysis. As a consequence, they use that extremity less and less, learning to use the unaffected arm in its place. Over time, disuse weakens muscles and most likely reduces the representation area of the affected part in the cortex"[32]. In order to avoid this outcome, one rehabilitation practice is to bind a patient's **unaffected** arm to his side, forcing them to use his afflicted arm for everyday tasks [35]. Even though this technique is effective, therapists find compliance difficult, as patients often abandon the binding in frustration. We postulated from these studies that perhaps stimulation of the fingers of persons with SCI that are not frequently employed due to "learned disuse" might provide sensory or motor improvements in the targeted fingers.

Tamaki and Rekimoto present another interesting method of using electrical stimulation. They have designed a device that controls fine movements of the hands and fingers using electrical stimulation applied through two bands wrapped around the wrist [87, 88]. See Figure 3. The research team demonstrated their system by using it to help train participants in playing songs on a Japanese instrument called a koto. Playing the koto properly requires the musician to perform intricate finger motions. The study performed by the team revealed that participants using their Possessed-Hand system made fewer errors and kept better rhythm on the koto than those who played without it. Participants were also able to distinguish which fingers were being manipulated, even though the fingers were not consciously controlled by the participant. The approach used in this study may aid in learning as the wearer, through the signals sent to the brain by the afferent nerves of the hand, "feels" the correct finger and hand motions to play a musical passage. Learning that takes place may be due

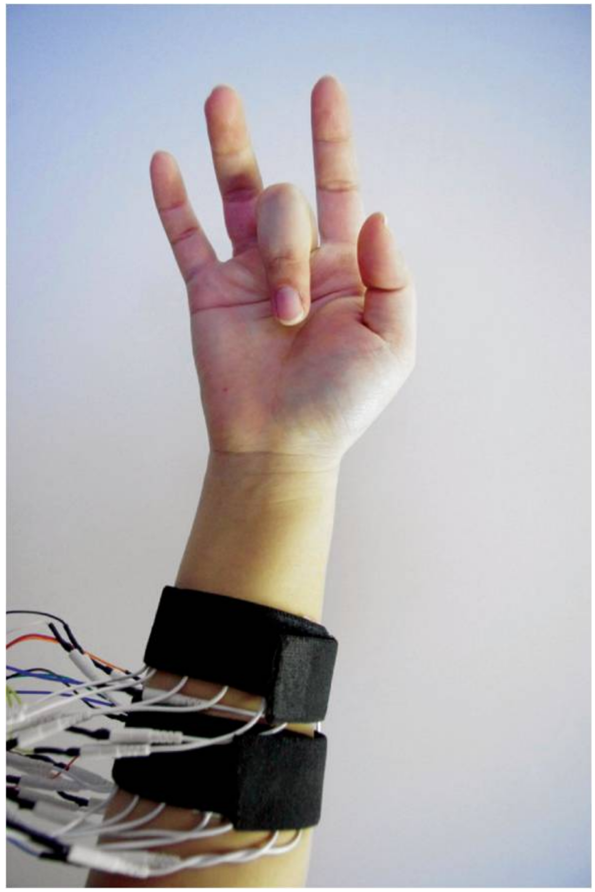


Figure 3: PossessedHand electrical stimulation bands fastened to the wrist. Used with permission.

to the correct awareness of the positions. The idea is akin to a teacher adjusting a student's hand and finger alignment to achieve proper placement, not unlike the use of vibration motors to aid in correct bowing and violin positioning of MusicJacket, discussed previously [89].

2.10 Brain Reorganization and Neuroplasticity

The brain is not a static structure. While we know now that there are regions of the brain that map to specific areas of the body and tasks (such as the visual cortex being the primary region for handling input from the eyes), we have also observed that the brain is able to reorganize itself in response to changes in the environment or due to injury. In his book *The Brain that Changes Itself*, Doidge illustrates the concept of environmental input forcing remapping of the brain. Brain imaging techniques may allow researchers to determine if physical changes are occurring in the brain in response to stimulus or due to illness or injury. Two of the most frequently used imaging techniques are Functional Magnetic Resonance Imagery (fMRI) and Positron Emission Tomography (PET). The fMRI method allows us to "view" changes in blood flow to various regions of the brain [69]. PET scans detect positrons emitted as a radiotracer breaks down in the body [79]. We believe that mechanical stimulation of the afferent nerves, which receive sensation and transmit it to the brain for processing, may cause physical changes in blood flow in the brain. We may be able to help positive brain reorganization to occur that may prove beneficial to a person with Spinal Cord Injury.

The brain reorganizes differently based on the type of Spinal Cord Injury. In the paper by Bruehlmeier, Dietz, Leenders, Roelcke, Missimer, and Curt "How does the human brain deal with a spinal cord injury?" the authors show using PET scans that not only does the brain of a tetraplegic map differently for hand activities than that of an uninjured person, but that a tetraplegic maps differently than a person classified as paraplegic. To demonstrate this phenomenon, the team recruited three groups of people for their study: a group of seven paraplegics, a group of seven tetraplegics who had some hand function, though limited, and a group of eight uninjured participants. They were required to be able to perform a hand task that had them using a joystick style device. All participants were asked to move a joystick in one of four possible directions (left, right, forward, backward), while their brains were mapped using Positron Emission Tomography (PET), where cerebral blood flow was used to determine the amount of neuronal activity during each exercise. This study was particularly interesting as it demonstrated that changes do take place in the brain after illness or injury that results in paralysis. In this case, it was found that the cortical area representing the hands encroached on the area typically employed for leg usage. The amount of activation in the leg area for hand activity was also found to be "significantly positively correlated with the number of neurally 'disconnected body segments"' [21].

The concept that the sensory modalities are not independent but work in concert to achieve perception is discussed by Shimojo and Shams [83]. The authors survey several studies to support this hypothesis. One study with ferrets showed that when the area of the brain generally responsible for processing somatosensory and auditory signals is ablated at birth, the retina took over these areas. These areas later activated when light was shined, stimulating the retina. This re-wiring of regions of the brain supports the concept of neuroplasticity [86]. Shimojo and Shams cite several studies that indicate plasticity in the human brain across modalities as well. In particular, persons who have gone blind demonstrated "auditory-evoked potentials" in the region of the brain generally responsible for processing visual stimuli (occipital) [59]. Shimojo et al. continue by examining how different sensory modalities can influence other modalities. This influence is evidenced by the 'ventriloquist effect' [50] in which a voice is perceived to be coming from a person moving his or her mouth, even though the actual speaker is located elsewhere. If the timing of the sound corresponds to the motion of the other person's lips, the illusion caused by the visual cues result in this effect. In their own study, Shimojo et al. demonstrated that when multiple modalities are presented to a participant, the stimuli that is the most discontinuous "becomes the influential or modulating modality" [83]. These studies support the concepts of neuroplasticity and integration of sensory modalities.

Visualization of a task may also aid in performance of the activity. For example, when preparing for a competition, a gymnast may imagine herself performing a routine perfectly just before actually doing it physically. Dr. Karolyn Babalola explored the concept of using visualization, or "mental practice" and the incorporation of a brain-computer interface (BCI) robot to aid in rehabilitation of persons who have suffered stroke [14]. The population of stroke patients who retain no ability to control their limb are often unable to undergo active rehabilitation, which moves the limb through range of motion and daily activities. The completely paralyzed of stroke patients may be served by a BCI-robot that is able to detect changes in brain activity of the wearer using a non-invasive electroencephalograph (EEG) cap that converts the imagined activity to commands for the rehabilitation robot. The BCI-robot allows the user to control the robot by thinking about the desired movement, causing the robot to then move the limb in the way imagined.

2.11 Piano Touch

Piano Touch, the forerunner of Mobile Music Touch (MMT), which we will introduce in much greater depth in the next chapter, was originally devised to demonstrate the concepts of Passive Haptic Learning and Rehearsal. Piano Touch is similar to a commercial system, Concert Hands. Concert Hands provides visual indications along with haptic cues to the user's fingers and wrists to guide the user to play songs on a piano [4]. Concert Hands demonstrates great potential as a product, but it is used only as an active learning system. It has not been used to try to demonstrate the feasibility of passive learning or as a form of rehabilitation. We wish to explore these concepts.

The basic premise of Passive Haptic Learning (PHL) is that one can learn or reinforce learned skills, such as playing simple songs on a piano keyboard, using the sense of touch and without having to focus on the activity. The concept of PHL was first explored by Kevin Huang using Piano Touch, which employed a wireless glove fitted with vibration motors in each of the fingers. A computing device, such as a laptop or smart phone, played a song and sent data about which finger to "tap" with vibration over Bluetooth. The wearer felt vibration on the appropriate finger to use to press a piano key. Early studies found that songs could be taught without actually having to practice them first - the wearer would have the melody “tapped out” in correct sequence on her fingers while performing an unrelated activity, such as taking a reading comprehension test. This passive practice seemed to result in a form of “muscle memory” which allowed the participants to play the song after this exposure [52].

Kohlsdorf et al. went on to further explore if the choice of distractor activity had an effect on the user’s ability to learn using the MMT system. They specifically investigated the impact of a memory game, watching a movie, and performing a walking task on a closed course. They found that the choice of activity in this case did not appear to have a significant effect on their ability to learn a new piano sequence [57].

Clinicians at the Shepherd Center, which specializes in spinal cord injury, viewed MMT as a possible interesting and engaging form of hand rehabilitation. The act of playing a musical instrument requires fine, dexterous movements of the hands and fingers, which provides a form of hand rehabilitation, and can also improve mood and sense of “well being” [77]. During a pilot study with two persons designated as quadriplegic, the participants experienced improvements in both sensory perception with the hands as well as their ability to perform motor tasks. Participants made some interesting comments such as the vibration “reminding” a participant of where his fingers were, as the individual had limited feeling in his hands. This phenomenon and other anecdotal comments about the vibration led the investigators to believe that perhaps the vibration was stimulating the afferent nerves of the hands, similar to what was suggested by Dimitrijevic et al. and Golaszewski et al. in their studies [33, 34, 43].

The goal of this dissertation is to show that vibration stimuli applied to the afferent nerves of the hands using a wearable device in the form of a glove will provide a greater improvement in sensation and hand function than just that resulting from active rehabilitation. Unlike traditional forms of rehabilitation, which tend to be tedious and repetitive yet still require the patient to actively participate in the activity to see benefit, we focus on passive rehabilitation. While Dimitrijevic's work has demonstrated the potential for electrical stimulation as a form of passive rehabilitation, we concentrate on vibration. If successful, our approach could be performed during the user's everyday life and without the messy and inconvenient conductive gel. For this work, we focus on participants with SCI who have injuries between C4 and T1 vertebrae and have the ability to move each of their fingers enough and with sufficient force to press the keys on an electronic keyboard and still have enough potential to show change, should it occur. Our larger goal, however, is to create a system that might help people by providing an interesting activity that is mentally engaging. A fascinating and creative outlet may not only encourage long-term rehabilitation, but may also improve mood and help with motivation. Finally, we extend the previous MMT/Piano Touch work by making the hardware much more rugged and reliable and use it to explore the concept of Passive Haptic Learning and Rehabilitation.

CHAPTER III

MOBILE MUSIC TOUCH

We built Mobile Music Touch (MMT), which we evolved from the original Piano Touch prototype designed by Kevin Huang, in order to evaluate the concepts of Passive Haptic Learning and Passive Haptic Rehabilitation. MMT is the primary tool used throughout all the studies in this work. It serves to deliver the vibration stimulus to the participant's hand in coordination with music. In this chapter, we will discuss the basic design and features of the MMT system and its evolution.

3.1 System

The Mobile Music Touch hardware consists of three elements:

- *Vibration motors*, or tactors, one fitted on each finger, dorsal side, just below the knuckle. The vibration motors built into a glove are exposed to view in Figure 4.

- *Bluetooth-to-serial module and microcontroller* to communicate with the computing device and to control the vibration motors.

- *Computing device* such as a laptop or cellular phone that plays the MIDI file for music and sends commands over Bluetooth to provide synchronized vibration to the tactors in the glove.

3.1.1 Hardware

The vibration motors are made by Precision Microdrives, model number 310-101, obtained via Sparkfun (see Figure 5). A spectrogram of the motor in operation is

Figure 4: Glove with vibration motors exposed.

presented in Figure 6. The Bluetooth-to-Serial module is a Roving Networks RN-41 (Figure 7). The microcontroller used in this system is an ATmega324, as pictured in Figure 8.

3.1.2 Function

A controlling device, such as a laptop or cellular phone, plays a selected song (in MIDI format). The correct fingering for the song is encoded in the lyric channel of

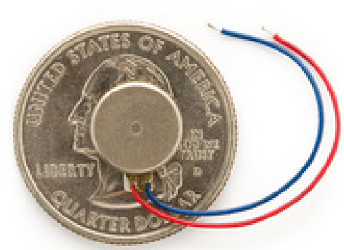


Figure 5: Vibration Motor

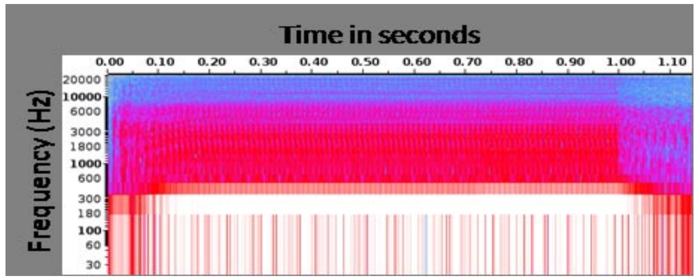


Figure 6: Spectrogram of Vibration Motor in Operation. Reproduced with permission [98].

Figure 7: Bluetooth to serial module RN-41 Image.

Figure 8: ATmega324

the MIDI file. As the song plays, the number representing the finger to be used to press the piano key is sent via Bluetooth to the glove. The Bluetooth radio receives the value and passes it to the ATmega324, which in turn raises the correct pin to high, sending 3.3V to the vibration motor, actuating it for a set period of time.

3.1.3 System Evolution

The MMT system has evolved over time to accommodate the needs of subsequent studies and user requirements. The original MMT was composed of a golf style glove and exposed hardware as depicted in Figure 9. This design was a good proof-of-concept but demonstrated some potential issues. The exposed hardware was not robust enough for repeated use in multiple studies. The glove shell, a golf glove, was not ideal for use by our target population, persons with Spinal Cord Injury (SCI), who typically use a manual wheelchair for mobility. We specifically wanted to ensure manual wheelchair users were accommodated with the MMT system, as this is the most specialized case within the population. Individuals with SCI who are able to walk would not require as much potential accommodation. In terms of hardware evolution, we moved away from thin, separate wires leading to each vibration motor from the hardware to a ribbon cable with a larger connector that was found to be more robust in daily use. We also wanted to minimize the need for wearers to have to handle the battery for charging. In order to accomplish this, we included a charging port. A key aspect of the redesigns was the 3D printed case. The case has openings for charging, an on/off switch, and a location to plug in the ribbon cable connector to the hardware. The case is then attached to the dorsal side of the glove with Velcro. The case contains all the hardware except for the wiring harness (ribbon cable and vibration motors), making it more compact and less prone to damage. We will discuss glove design further in the Chapter 5.

Figure 9: Original MMT Glove Design.

CHAPTER IV

PASSIVE HAPTIC LEARNING

Most rehabilitation activities are active in nature, requiring the focused participation of the injured person. Our goal was to evaluate the MMT system as a possible hand rehabilitation method using Passive Haptic Rehabilitation (PHR). PHR may be achieved by employing tactile stimulation that brings about beneficial changes without the active engagement of the injured person. Several studies have shown some possible rehabilitative benefits using haptics to bring about improvements in persons with injuries involving the central nervous system. However, we sought to create a new rehabilitation method, and to couple the activity with the learning of a new skill, such as playing songs on a piano keyboard. In this chapter, we examine Passive Haptic Learning (PHL) more carefully. We have described PHL as learning a new skill or activity without active focus and through the sense of touch while performing another, unrelated activity. To better take advantage of the effects of PHL, we designed a study to have participants wear the MMT glove several hours a day. We first needed to determine if audio is necessary for the learning benefits or if vibration alone might be sufficient. We wished to avoid using audio, as it might prove too distracting when performing other activities, such as talking on the phone. To this effect, the following study provides quantitative data about the effect of four conditions intended to reinforce active learning sessions. In truth, this process might be better called the Passive Haptic Rehearsal of music. The four conditions for this study are: 1. no stimulation (control), 2. audio alone, 3. vibration alone, and 4. vibration with musical accompaniment. Our goals are to:

- *Study the effect of each PHL condition (control, audio alone, vibration alone,*

Figure 10: MMT PHL demonstration on CNN. September, 2010

and vibration with music) on a person's ability to retain what is learned during an active learning session.

- *Create an experimental design* that can be used for other studies of the same type.

4.1 Motivation

Hopefully, gaining the ability to play the piano will encourage continuing the activity, further strengthening the player's abilities. We demonstrated the MMT system to teach a novice how to play "Ode to Joy" after just 30 minutes of exposure to the audio and vibration; it was featured on CNN's the "Big I" in 2010 [3], as pictured in Figure 10.

A previous study, conducted by Kevin Huang, sought to determine the amount of reinforcement provided by vibration coupled with music versus music alone [51]. His work demonstrated that vibration coupled with music allowed users to better retain the musical phrases learned on the piano than those who only listened to the song as a form of reinforcement. Huang's experiments involved 30 minutes of passive learning. However, we wanted to have users wear the MMT glove for several hours throughout their normal day. The vibration may not be particularly distracting, however hearing a song played over and over during this time may interfere with normal activities, such as writing, checking email or interacting with people socially. We sought to demonstrate that music learned on the piano may be reinforced adequately by vibration only versus vibration with music. If we found no meaningful difference between vibration alone and audio+vibration, we would have some justification in attempting to use vibration alone as a reinforcing stimuli for longer term use of MMT for PHL and potentially for PHR. We also desired to show the potential contribution to retention of learning that vibration alone may provide.

4.2 Pilot Study

4.2.1 Experiment

To determine the effects of various forms of stimuli on the ability of a subject to retain what is learned during a PHL session, we examined two independent variables with a 2x2 Latin-square within-subjects study design. The first variable is stimulus method. The second variable is song selection.

Our two stimulus conditions were vibration alone and audio+vibration. We used two songs for this study, a selection of 45 notes from "Jingle Bells" (the dashing through the snow verse, not the chorus), and a 44 note passage from "Amazing Grace." These songs are considered to be of equal difficulty, rated as Level B in the song book that accompanied the Casio electric piano used for this study [1]. Similar to the study conducted by Kevin Huang, participants played these songs using only the right hand, and both phrases were in the key of C [51].

We trained participants to play one of the two song passages by teaching them one song phrase at a time (each song passage was broken into smaller phrases that allowed it to be learned in steps, rather than all at once). As the participant successfully managed to play a phrase, we moved on to the next phrase, and so on, until the participant could successfully play the entire passage without error. We first played the phrase so that the participant could hear the song, see LEDs on the electric piano keyboard light corresponding to the key to press, and feel vibration in the finger that should be used to press the key. The participant then attempted to repeat the phrase without any cues (no music, no LEDs and no vibration; just play from memory). Once the participant played the song once through correctly on his own, we then moved into the next phase. During this time, all subjects completed a 30 minute GRE reading comprehension task while experiencing either the vibration or the audio+vibration stimulus from the MMT system. They encountered one condition with one song and the other condition with the other song at a later time.

During the 30 minute GRE test with the vibration only condition, the participant felt the song being "played" on the glove, with the vibrators tapping each finger that would be played in sequence. Participants experiencing the audio+vibration condition would "feel" the song being played via vibration and also hear the song playing at the same time from the computer speakers. At the end of this distractor task, the participant was asked to play the song passage without any cues. They were given three attempts. For each attempt, we scored the number of errors the participant made in his or her playback. For this study, we counted an error when the participant played a wrong note. We employed a Dynamic Time Warping algorithm, discussed below, to determine these values.

4.2.1.1 Dynamic Time Warping Algorithm

Each participant's performances were evaluated using a Dynamic Time Warping (DTW) algorithm, which allowed us to compare two musical passages that might differ in tempo. We used the DTW Algorithm twice on each passage; once to account for errors in note sequences (considering pitch) and the second time for variances in rhythm. It helped account for errors of substitution, insertion, and deletion. DTW evaluates the costs associated with various types of errors and attempts to minimize the costs, while finding the optimal match between two sequences. The costs employed in this analysis are

1. cost of a difference in note pitch ($cost_n$)

2. cost of a space in the first phrase ($cost_{space1}$)

3. cost of introducing a space in the second phrase ($cost_{space2}$)

We considered each potential type of error as equal for this analysis and assigned each a value of 1. This metric is similar to the ISO standard for speech recognition accuracy. Consider the following:

Correct Sequence: C D E F F F B C C D E F - F F F E F - F - E C D - F D F

Actual Performance: C D E - F F B C C D E F - F B F E F - F B E C D - F D F

In the above example, the top line is the original passage, as it would be played correctly and, in this case, we used the actual passage D from Figure 16. The second line is an example of an attempted performance of the passage. We can see that the participant's error score for this performance would be 3. The participant deleted an F, substituted a B for an F, and inserted a B where no note should have been played.

The DTW algorithm was also used to evaluate a participant's performance of a song's rhythm versus a given standard performance. Rhythm is analyzed by comparing the duration of each note. For this run of the DTW algorithm, we do not consider pitch of a given note, only duration in milliseconds. We must change the costs used in the pitch analysis to those listed below:

1. cost of pairing A[i] with B[j] = ABS(duration of A[i] - duration B[j]) where A and B are passages, i and j are indices of the notes of the passages, and ABS is the absolute value ($cost_m$)

2. cost of a space in A ($cost_{spaceA}$)

3. cost of a space in B ($cost_{spaceB}$)

The calculated values for rhythm are the total cost as expressed in mismatched milliseconds.

4.2.2 Results

Using a paired t-test, we compared the audio+vibration condition with the vibration only condition. All subjects had practiced the song until they had 0 errors before the passive rehearsal session; after the session they made three more attempts. Using a paired t-test, we compared the errors made in the vibration only condition with those in the audio+vibration condition. See Table 1. There was no meaningful difference between the conditions for any of the three attempts ($ATT1mean_{vib} = 2.08$ vs. $ATT1mean_{aud+vib} = 2.25$, p = 0.74), ($ATT2mean_{vib} = 1.08$ vs. $ATT2mean_{aud+vib} = 0.92$, p = 0.76), ($ATT3mean_{vib} = 0.42$ vs. $ATT3mean_{aud+vib} = 0.92$, p = 0.11). We also compared the average of the three attempts ($AttAVGmean_{vib} = 1.19$ vs. $AttAVGmean_{aud+vib} = 1.36$, p = 0.60), and finally the best of the three post attempts: ($BESTmean_{vib} = 0.25$ vs. $BESTmean_{aud+vib} = 0.25$, p = 1.00). We found that there was no statistically significant difference in any of these cases. We also evaluated the participants' GRE scores. Using the 2-tailed, paired t-test, we found no meaningful difference between the values ($GREmean_{vib}$=22.58 vs. $GREmean_{aud+vib}$=22.67, p = 0.92).

4.2.3 Discussion

When considering the raw data we found an interesting trend. Vibration alone seemed to have a better effect when used for Jingle Bells than it did for Amazing Grace. The songs are considered to be of similar difficulty. However, one possible variation between the two songs is that of note length. The version of Jingle Bells we used has

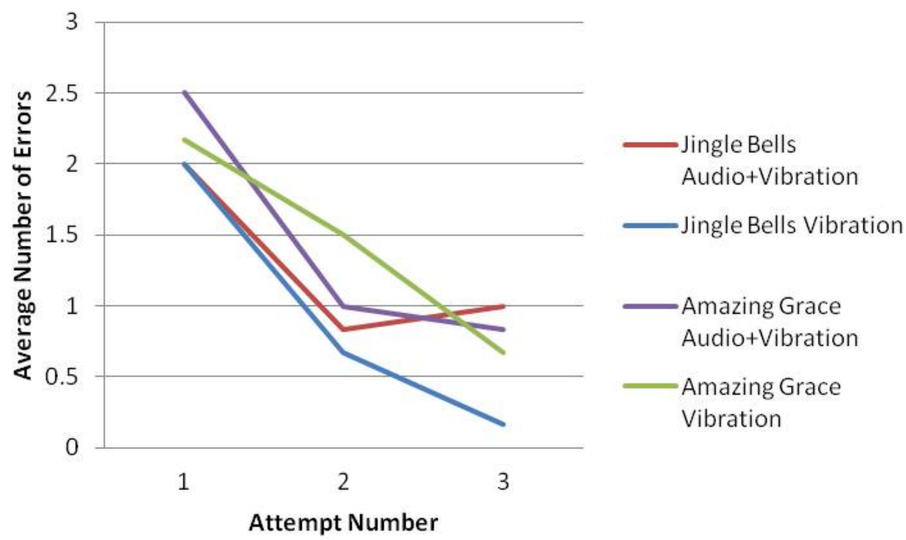


Figure 11: PHL Graph Vibration and Vibration + Audio Conditions for Amazing Grace and Jingle Bells.

Table 1: Passive Haptic Learning Study Raw Data. JB = Jingle Bells; AG = Amazing Grace.

Subject	Condition							
	Vibration				Audio+Vibration			
	Song	Err1	Err2	Err3	Song	Err1	Err2	Err3
1	JB	3	1	0	AG	3	5	0
2	AG	2	5	2	JB	2	2	1
3	AG	1	0	1	JB	3	0	2
4	JB	0	0	0	AG	0	0	0
5	JB	1	0	0	AG	0	0	0
6	AG	2	1	0	JB	2	2	1
7	AG	0	1	0	JB	1	1	0
8	JB	0	0	0	AG	0	0	2
9	JB	8	0	1	AG	12	1	2
10	AG	5	1	0	JB	4	0	2
11	AG	3	1	1	JB	0	0	0
12	JB	0	3	0	AG	0	0	1
Avg		2.08	1.08	.42		2.25	.92	.92

notes generally of all the same length. Amazing Grace has notes of varying length. It is possible that songs with more complexity, like those represented by Amazing Grace, may require the music to reinforce what is learned with the vibration and may warrant further exploration in future studies. In order to avoid possible issues created by variances in song selection, we will use newly generated tunes in our next Passive Haptic Learning study. In the follow-on study, we will explore four conditions: control (no intervention), audio only, vibration only, and audio+vibration with music. We seek to determine the possible contribution to learning and retention of each of these conditions.

4.3 Full PHL Study

The pilot study helped us to refine our procedures and led us to realize that we needed to assess all four conditions, as discussed above. We did note that the song selection in the pilot led to some cultural bias for those not familiar with the songs. We hypothesize that the three non-control conditions (audio only, vibration only, audio+vibration) will result in lower error scores than the control condition. We expect the tactile conditions of vibration only and audio+vibration will show significant improvements in error scores over just the audio condition or the control condition.

4.3.1 Experiment

We first decided to ensure internal validity by generating our own songs. We sought phrases that would still be perceived as "musical." In order to create these songs, we used the program "Wolfram Tones." This software allows the user to enter various constraints and then generates "musical" passages. We also desired to eliminate lateral hand motion required by many existing tunes. We constrained the generation of these songs to match the five fingers of the right hand to five keys on the piano; they are mapped as seen in Figure 12.

We conducted a pilot study to assess an appropriate length for the phrases. The

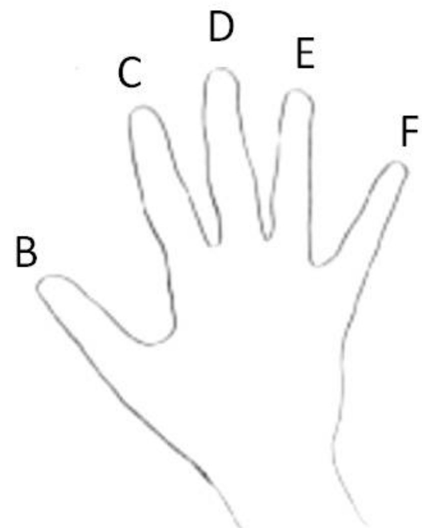


Figure 12: Hand Note Mapping

Figure 13: Random Song A

new phrases we created were unfamiliar and were consequently more difficult to learn. These new phrases also did not have any repetition, another difference from the pilot songs of “Amazing Grace” and “Jingle Bells.” Based on the poorer performance of subjects during piloting using these more difficult songs, we decided to use shorter phrases, making them 22 notes in length. The four passages we generated are shown in Figures 13 through 16.

The study design was a modified Latin Square with four different song passages and four separate conditions. Each participant attended four one hour sessions, none of which were conducted consecutively in order to avoid fatigue. A participant could

Figure 14: Random Song B

Figure 15: Random Song C

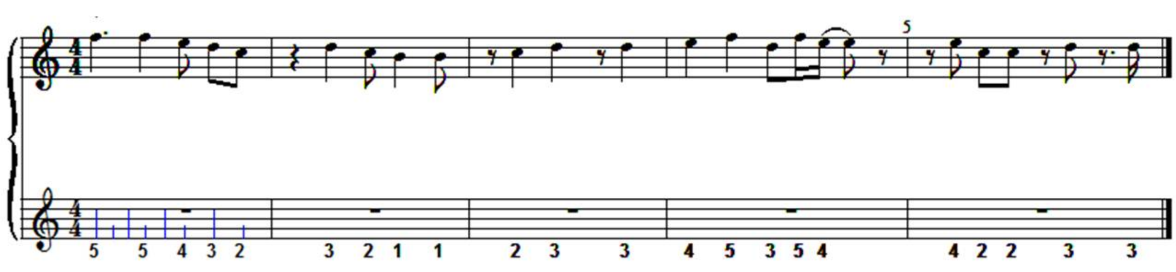


Figure 16: Random Song D

perform two sessions in one day if there was at least a one hour break between sessions. The sessions proceeded as follows:

Prior to the first session, we had the participants complete a pre questionnaire to record the amount and type of musical training they already had going into the study. A sample can be found in Appendix C. We did not accept into the study anyone who had formal piano training, as it was found in a previous study that these individuals had a great deal of difficulty adapting to and accepting the training provided by the glove. Such subjects may have suffered from interference with previously learned methods of playing, or they may have found the more amusical phrases used in the study counterintuitive [52]. The participant put on the MMT glove; the investigator played the entire passage one time through, allowing the participant to hear the tune, feel the vibration and see the LEDs light in the correct sequence on the piano keyboard. Next, we focused the user on small portions of the melody. Figures 17 through 20 shows Song A broken into four phrases. Each phrase was played using the MMT system for the participant (with vibration through the glove, LEDs lighting the correct notes). The participant then attempted to repeat it without assistance, from memory. Initially, we conducted this experiment like we did the pilot. The participant was given the chance to repeat this sequence over and over for each phrase and compound phrase until he played that phrase perfectly; only then did we move on to the next phrase or combination in the study design. However, because we had chosen to shorten the phrases, we observed that most participants reached a ceiling effect, memorizing the songs and then not forgetting them at all during the 30 minute period. In an effort to combat this effect, we chose to limit participants to a finite number of attempts for each phrase. The evolution of this study design is depicted in Table 2.

The last error score for playing the entire phrase during the practice session was used for comparison with the attempts at playing the phrase after the passive learning

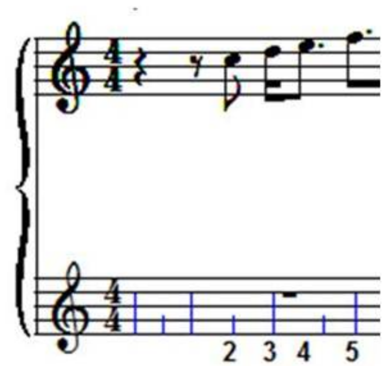


Figure 17: Song A Phrase 1

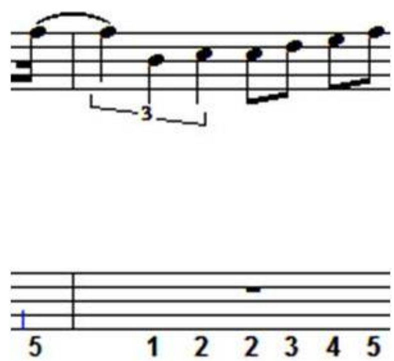


Figure 18: Song A Phrase 2

Figure 19: Song A Phrase 3

Figure 20: Song A Phrase 4

Table 2: Passive Haptic Learning Study Design Evolution.

Passage Title	Number of Repetitions		
	Initial Design	Interim Design	Final Design
Phrase 1	Until Perfect	1	1
Phrase 2	Until Perfect	1	1
Phrase 3	Until Perfect	1	1
Phrase 4	Until Perfect	1	1
Phrases 1 and 2	Until Perfect	4	5
Phrases 3 and 4	Until Perfect	4	5
Phrases 1-4	Until Perfect	8	10

sessions. This practice was consistent with the pilot for which the last practice was the participant's "zero" attempt, in which he played the passage once without any errors.

The participant then took a quantitative GRE for a 30 minute period. Four different GRE tests were used and were given by computer, ensuring the participant received different questions each session. During this 30 minute "forgetting" period, the participant experienced one of the four conditions from MMT: nothing (control), audio only, vibration only, or vibration and audio. In the three non-control conditions, the audio and/or vibration repeated continuously during the period. Then, when the GRE period was complete, the passage was played once more, without vibration cues. The participant was asked to play the passage three times without any assistance. We decided to use the best of the three post attempts in order to reduce possible outliers caused by a participant who became flustered on a single given attempt. To determine the error scores, we took the difference of the best of the three post attempts and the last score before the 30 minute quantitative GRE period. We used a MIDI keyboard to record the participant's performance. The participant then completed a post questionnaire (see Appendix D) and the NASA TLX assessment (see sample Appendix E), evaluating their perceived load specifically during the 30 minute quantitative GRE period while experiencing one of the four conditions.

4.3.2 Results

We found that the four conditions, control, audio, vibration and audio+vibration, had distinct differences in their average number of errors. Audio+vibration was found to demonstrate a statistically significant improvement in error scores versus the control case, with a p-value of 0.02 (one-tailed paired t-test) and an effect size of 0.16 (large effect). The difference in means for vibration alone proved marginally significant when compared to control with a p-value of 0.05 (one-tailed paired t-test) with an effect size of 0.11 (moderate effect), and audio alone fared slightly worse when compared to control with a p-value of 0.08 (one-tailed paired t-test). We used a one-tailed test as we are examining improvement from the control condition, not difference. To determine the contribution of each condition, we took the difference of the best error score before the 30 minute GRE test and the best post-GRE error score. As was expected, the control condition resulted in the highest increase in the number of errors the participants made, with an average increase in errors of 1.17. The audio only condition showed an average increase in 0.54 errors. Both the audio+vibration and the vibration only conditions averaged an increase in errors of 0.33 over the 24 participants (see Figure 21). Raw data may be found in Table 8. The 30 minute GRE test causes distraction from the learned passage resulting in a period of "forgetting" which the PHL effect may be helping to counteract. Note that a smaller change in this study is beneficial, as that indicates fewer errors being made after the GRE test period than before. For example, a participant might make 5 errors before the GRE and then only make 3 errors after the vibration only intervention, which may indicate that the intervention is aiding in learning or the retention of learning. The trends we are observing show that the three conditions of audio, vibration, and audio+vibration all help reduce the difference in number of errors after the GRE period; however, vibration alone or vibration with audio provides the greatest reduction in errors. We then considered these results along with those of the NASA TLX surveys. The NASA TLX survey has participants rate an activity in six workload categories: mental, physical, temporal, performance, effort, and frustration on a scale with 21 gradations [46]. Higher values are considered to be a higher "load" on the survey and, in this case, would be considered more detrimental. Of these six categories, we were most interested in effort and frustration, as they might best reveal if the condition was particularly distracting to the user. For this study, we asked the participants to rate their perceptions using the NASA TLX for the 30 minute period when they were

Table 3: PHL Rhythm Averages by Condition

Condition	Average (milliseconds)
Control	2901
Audio	2777
Vibration	2838
Aud+Vib	2855

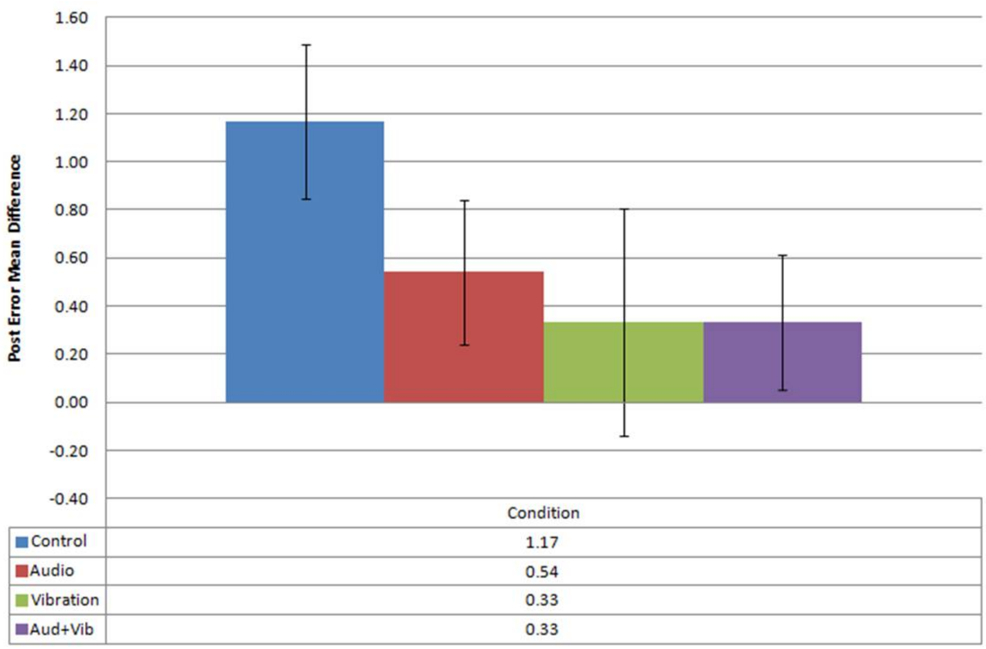


Figure 21: Average Note Error Difference by Condition

performing the GRE quantitative test and receiving one of the four conditions. We did analyze rhythm data as well between the conditions, as shown in Table 3, and noted no meaningful difference between the values.

Considering the values in Table 4, it is clear that the conditions of vibration and audio+vibration appear to have higher load factors than just audio alone. However, when we look particularly at the two cases that most point toward distraction, effort and frustration, we found no significant differences between the averages of the conditions for Effort, as seen in Figure 5. Participants assigned a high rating for frustration when comparing the audio+vibration condition (average rating of 11.25) to control

Table 4: NASA TLX Overall Values.

Cond. 1	C1 Mean	Cond. 2	C2 Mean	p-value
Control	9.85	Audio	10.51	0.22
Control	9.85	Vibration	11.17	0.03
Control	9.85	Audio+Vib	11.39	0.01

Table 5: NASA TLX Effort Values.

Cond. 1	C1 Mean	Cond. 2	C2 Mean	p-value
Control	12.83	Audio	12.67	0.77
Control	12.83	Vibration	12.79	0.96
Control	12.83	Audio+Vib	13.46	0.39

Table 6: NASA TLX Frustration Values.

Cond. 1	C1 Mean	Cond. 2	C2 Mean	p-value
Control	8.50	Audio	9.13	0.52
Control	8.50	Vibration	10.75	0.05
Control	8.50	Audio+Vib	11.25	0.01

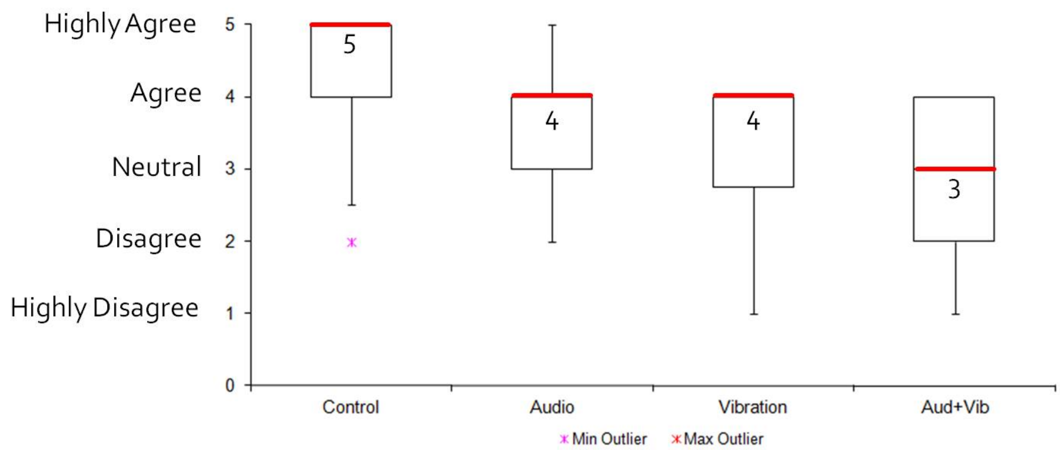


Figure 22: Post Questionnaire. Ability to focus on the GRE by condition.

(average rating of 8.5) resulting in a two-tail paired t-test of p = 0.01 (see Figures 6 and 23). We next considered responses on the post questionnaire. This survey was administered to all participants after each of the four conditions in each session. Not all questions apply to all conditions, as there is a question that specifically asks about audio, which does not apply to the control condition. Of these questions, we were particularly interested in finding out how well the participants were able to focus on the GRE quantitative distractor task. We compared the medians of each of the three non-control conditions to thte median of the control condition and found that they all show a statistically significant difference ($p < 0.05$ using a two-tailed paired t-test; $POSTmedian_{control} = 5$, audio $POSTmedian_{audio} = 4$, vibration $POSTmedian_{vibration} = 4$, and audio+vibration $POSTmedian_{audio+vibration} = 3$). The median values showed a distinct shift from a perceived "highly agree" ability to focus on the GRE to "Neutral" when we reach the aud+vib condition. This clear downward trend is depicted in Figure 22. These observations support our intuition of using vibration only for the future Passive Haptic Rehabilitation study (discussed in the next chapter). If the glove is too distracting, it will interfere with activities to the point that it may no longer be acceptable to the user for daily, extended wear (2+ hours per day).

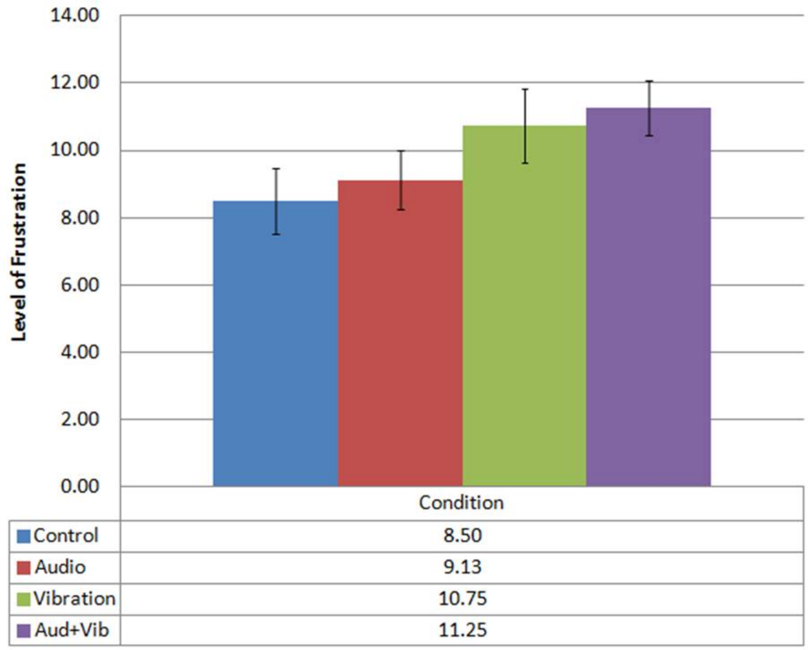


Figure 23: Participant average frustration levels during GRE by condition

Table 7: Quantitative GRE Average Scores by Condition.

Condition	Avg GRE Score
Control	435.83
Audio	455.42
Vibration	446.25
Aud+Vib	444.17

4.3.2.1 Quantitative GRE Comparison

The 30 minute quantitative GRE test served in this study as the distractor or active task. We evaluated the scores of each participant on the test to determine if any of the four conditions may have a significant effect on active task performance. The average GRE test scores are displayed in Table 7. When the average GRE scores of each condition were compared to the control GRE average none was significantly different, revealing that the participants appeared to have given a similar amount of attention to the GRE test regardless of the condition applied.

Table 8: Passive Haptic Learning Study Error Raw Score Data.

Sub.	Condition											
	Control			Audio			Vib			Audio+Vib		
	Pre	Post	δ	Pre	Post	δ	Pre	Post	δ	Pre	Post	δ
1	5	9	4	4	3	-1	6	6	0	7	8	1
2	3	4	1	6	7	1	6	7	1	5	4	-1
3	7	10	3	8	8	0	1	2	1	6	3	-3
4	1	3	2	6	5	-1	6	5	-1	6	6	0
5	1	1	0	0	0	0	0	0	0	0	0	0
6	6	8	2	6	6	0	8	11	3	7	11	4
7	2	3	1	1	5	4	4	1	-3	1	3	2
8	1	2	1	3	4	1	6	2	-4	4	7	3
9	5	1	-4	0	0	0	3	2	-1	5	4	-1
10	0	0	0	2	3	1	2	1	-1	0	0	0
11	2	6	4	3	4	1	1	3	2	8	8	0
12	0	1	1	0	1	1	2	2	0	4	4	0
13	5	6	1	8	10	2	10	12	2	3	4	1
14	7	9	2	4	8	4	2	2	0	1	2	1
15	8	9	1	6	4	-2	6	12	6	2	1	-1
16	2	3	1	7	9	2	9	7	-2	5	4	-1
17	10	12	2	2	1	-1	7	7	0	6	6	0
18	1	2	1	0	0	0	0	1	1	0	0	0
19	0	2	2	2	3	1	2	8	6	4	5	1
20	6	6	0	6	6	0	8	7	-1	5	5	0
21	7	7	0	1	0	-1	1	1	0	5	5	0
22	3	5	2	6	7	1	4	4	0	5	6	1
23	2	3	1	10	11	1	3	2	-1	8	9	1
24	0	0	0	1	0	-1	3	3	0	0	0	0
Avg.			1.17			0.54			0.33			0.33

4.3.3 Discussion

This study revealed that audio alone, vibration alone, and audio+vibration all result in an overall lower error score than the control case. This result suggests that such interventions are worthwhile for learning and retention. While the audio+vibration case did achieve statistical significance for average error change rate, this condition also achieved a statistically higher frustration rating when compared to the control condition. Vibration only achieved marginal significance for the error change rate, but had lower NASA TLX scores, suggesting less distraction. With the proposed PHR study design requiring the user to wear the MMT glove for 2+ hours per day, we must consider not only the glove's effectiveness, but also its potential to cause unwanted distraction, rendering it undesirable for long-term wear. We did observe that each of the conditions does provide some benefit by reducing the error rate over the control case. This finding is significant, as it allows us to move forward with the Passive Haptic Rehabilitation study using vibration only, eliminating the need for participants to listen to the song in a loop while performing their daily activities. We feel the resulting system will be more tolerable and welcome in daily life.

4.3.4 Conclusion

This chapter demonstrated the usefulness of the MMT system to aid in learning and retention of simple songs on the piano. In the next chapter, we will apply the concept of PHL using the MMT system as a possible form of hand rehabilitation. The PHL studies justify the use of vibration alone instead of having to incorporate audio to aid in learning and retention.

CHAPTER V

GLOVE DESIGN

The following glove design studies provide qualitative data about the suitability of various glove features for our target population, specifically persons with Spinal Cord Injury (SCI) who use a manual wheelchair for mobility. The studies:

- *Provide a set of features appropriate for use in a glove for persons with SCI.*
- *Determine user perception of the effect of vibration on everyday activities.*
- *Describe an experimental design* that can be used for other studies of the same type.

5.1 Motivation

In order to evaluate the effectiveness of the MMT system as a form of hand rehabilitation in people with SCI, we had to ensure the gloves that participants would be asked to wear would be suitable for persons who use a manual wheelchair. The original MMT glove was a modified men's large golf glove. This design, dubbed the "Golf Style Glove" had the fingertips removed in order to provide better finger perception for the wearer. While this glove worked well enough in controlled laboratory settings, during the initial study, we identified some potential problems with it. The participants in this pilot study had a difficult time getting the glove on and off, and the lack of multiple sizes was a potential issue as well. There was also the issue of the vibration itself. We had to ensure that the vibration would not greatly impact the normal routine of the wearer; a key concern as we would be asking participants to wear the glove for 2-4 hours a day, several days a week. During the course of these iterative design studies, we refined our features based off of feedback from the participants.

5.2 Experiment

We conducted two iterations of a user field study to examine these issues. For the first study, we asked three people with Spinal Cord Injury (SCI) to wear each of three different glove designs and assess the features. We took our findings from this first study, devised three new glove designs, and then had three different tetraplegic participants evaluate the new designs. Both studies also integrated an automated vibration pattern set to the tune of "Jingle Bells" to allow participants to comment on the vibration and its effect on their daily activities.

5.2.1 First Glove Design Study

The first glove study was conducted in order to discover a set of features that would best serve our target population, specifically persons with SCI. The gloves tested include

1. The Golf Style Glove was the original glove used in initial studies of the MMT system. See Figure 9. It is simply a modified men's large golf glove. The modification entails the simple removal of the fingertips to allow for greater sensation for the wearer.

2. The Open Flap Glove is a modified glove that has the finger tips cut off and longitudinal vents down both sides. The vents enable the glove to be opened very wide to assist in donning the glove on "contracted" hands. Additionally, small lateral vents have been cut into each finger above the knuckle to allow for proper motor placement. The wires are contained by a Velcro strap, and the hardware attaches to a Velcro patch near the wrist.

3. The Velcro Finger Glove is also a modified glove, but the entire ventral side of the glove has been removed and Velcro straps wrap around the user's fingers. Wire management is achieved through two sets of external straps.

We performed a user study to determine which glove design was most suited for regular/everyday use by people with SCI. We employed this type of study to better understand the user experience. The participants in the study were three individuals with tetraplegia who played together on a wheelchair rugby team. The benefit of using these subjects was that they are considerably active with their hands and would put the gloves through rigorous testing. Each participant was given all three glove designs and instructed to wear each design six hours a day for two consecutive days while performing normal daily activities. Following each glove usability session, participants were asked to complete a nineteen question satisfaction survey assessing the performance of both the glove and hardware components. The survey contained both structured and open-ended questions with the intent of obtaining standard measures of functionality for the glove as well as personal experiences that may dictate further design. To emulate a system that interfaces with a hand-held music player or a mobile phone, we pre-programmed the glove to keep generating the finger vibrations for the song "Jingle Bells" every 100 seconds. The glove, when switched on, will wait for a Bluetooth connection for one minute. If it does not find a connection, it automatically starts playing "Jingle Bells" in vibration form. Each finger vibrated for 200 milliseconds and paused for another 200 milliseconds before vibrating the next finger.

The participants responses to the surveys have been compiled, categorized by glove design, and are presented in Figure 24, Figure 25, and in the text below. Figure 24 shows preferences, with green checks showing preferred features and red 'x's' indicating features that received negative reviews from participants. The questionnaire can be viewed in Appendix A. Due to the small subject population, it is inappropriate

Figure 24: Comparison chart of glove designs evaluated in first glove field study.

to make statistical inferences from this data, but the feedback is helpful in making design considerations for future studies.

- *Glove 1: Golf Style Glove:* The golf style glove was the design of the glove used for the pilot study [52]. The golf style glove design received satisfied to very satisfied reviews with respect to comfort, fit, and grip. The participants experienced difficulty donning the glove as they did not have assistance. The glove itself was not considered irritating, and the weight was only slightly noticeable. However, one user expressed dissatisfaction in the glove material as it would easily wear from continual contact with the wheelchair wheels. The glove itself was considered to be of little hindrance to daily activities. User feedback about the hardware was consistent across all designs. Exposed wire, hardware size, and hardware slippage were all noticeable and contributed to maneuverability problems and hindered daily activities. The hardware produced good vibration cues with participants being able to distinguish the cues from the individual motors. The hardware was also listed as not working reliably during one participant's

	Good Grip	Easy On/Off	Durable
Golf Style Glove	✓✓	✗	✗
Open Flap Glove	✗	✓	✗
Velcro Finger Glove	✗	✓✗	✗

Figure 25: Comparison of glove designs from first glove field study, by feature.

session as the wire leads to the batteries kept detaching. Another participant described feeling higher intensity in vibrations in the fourth and fifth fingers but was uncertain whether it was due to a hardware issue or hypersensitivity in the fingers.

- *Glove 2: Open Flap Glove:* The open flap glove received mixed reviews and proved to be highly dependent on individual preference and the severity of a participant's tetraplegia. The feedback indicated that the users were dissatisfied with the material selection, as the slick fabric did not afford gripping and thus hindered manual wheelchair handling. Participants also gave the glove unsatisfactory reviews with respect to the durability of the fabric and the fasteners. User comfort ranged from "dissatisfied" to "very satisfied," and all three users were satisfied with overall fit. The users did not find the glove to be irritating or the weight to be too noticeable. Furthermore, participants stated that putting on and removing the glove posed some to no difficulty as users employed teeth to don, adjust, and secure the glove. As per the hardware comfort and software performance, no feedback was received from one participant due to hardware failure. The two remaining participants were unhappy with the wire exposure, though the ribbon cable was securely sewn to the glove with some slack left to account for finger bending and extension. The size of the hardware proved to be another point of dissatisfaction with the participants. General bulkiness and an insecure forearm mount resulted in continual slippage. Troubles with bulk and security contributed to maneuverability difficulties and impedance with daily activities such as hygiene tasks and chair pushing. In two instances, participants indicated the hardware was irritating to the hand or arm. The performance of the glove was rated well for administering clear, distinguishable vibration cues. However, the overall ratings for hardware reliability varied as the wire leads to the batteries kept detaching in one of the gloves.

- *Glove 3: Velcro Finger Glove:* While the Velcro finger glove received mixed reviews for comfort, fit, and durability, it was clear from the remaining survey responses and user commentary that this glove was the least preferred of the three designs. All users strongly disagreed that the glove was easy to put on; however, some participants indicated that glove removal was easy. The weight of the glove itself was not considered to be irritating, but the users did state the glove was noticeable when donned with hardware. Two participants indicated that the glove irritated or rubbed the hand/forearm, while all participants considered the hardware to interfere with daily activities. The users responded that vibration motors were easily discernible, but there was some feedback on lower vibration intensity due to shifting of the fingerlets. One user indicated that the hardware performance was insufficient as the wire lead to the battery pack detached. We also observed some issues that were mentioned by the participants with SCI in reference to using the MMT with a manual wheelchair. Problems encountered included hardware slippage down the arm, entangling with the wheelchair, lack of grip or no grip on the palm of the gloves to provide traction while pushing the wheels of the wheelchair, and finally difficulty putting the glove and hardware assembly on by oneself.

Overall Assessment. No single glove design was the most preferred by all users. Instead, select features of each particular glove design proved to be desirable. After reviewing the feedback, it was clear that one glove design may not be appropriate for accommodating the different levels of tetraplegia. Thus, the severity of the disability as well as particular user needs have to be taken into account when deciding which features to incorporate into a new glove design.

The glove design process is iterative in nature. This first iteration revealed several issues and concerns that had not been known going into this study. Based on these findings, we conducted a second iteration of this study with refinements to the glove designs based on user feedback. Additional changes include reducing hardware size, implementing the housing compartment with the working system, mounting the hardware on the wrist rather than the arm, selecting a glove with more tractional material, better wire management (including full stitching to the base of the vibration motors) and exploring the possibility of using conductive thread for optimal wire management.

5.2.2 Second Glove Design Study

For the second iteration of the glove design study, we decided to devise three designs to be tested based on the feedback from the first study. One of the key changes was that of the actual glove shell. We knew that some people who use a manual wheelchair routinely wear gloves to reduce wear on their hands and improve traction between the hands and wheels. We asked people with SCI and clinicians what brands and types of gloves are favored. The brand we heard repeatedly was Harbinger, a type of athletic glove used generally for lifting weights. We conducted an informal trial

Figure 26: Harbinger Big Grip II glove.

Figure 27: Harbinger Pro glove.

Figure 28: Harbinger FlexFit glove.

and survey of persons with SCI of three styles of the Harbinger glove, the "Big Grip II" (Figure 26), the "Pro" (Figure 27) and the "FlexFit" (Figure 28); the resounding preference was the "FlexFit." The "Big Grip II" was considered too bulky, with a very heavily padded palm that greatly reduced feeling through the fabric as well as having a "stiff" feel to it. The "Pro" was rated second in the selection due to bulky palm fabric and longer fabric covering the base of the fingers. The "FlexFit" was still durable, but with minimal bulk across the palm and, true to its name, allowed the most motion, and the fabric had the highest degree of flexibility of the three options. Another major change was that of the hardware. We greatly reduced the size of the hardware and integrated a port for charging the battery without removing it from the device, as seen in Figure 31. We also created a 3D printed case for the hardware and battery that was small and light enough to be mounted to the back of the glove shell with Velcro. To avoid wire entanglements, we also embedded the wiring harness into the seams of the glove shell and tacked them with hand sewing to minimize wire entanglements, a common complaint during the first iteration of the glove design study. The hardware and box were attached to the back of each glove using Velcro. We used the following three glove designs for this study:

- *Unaltered Glove:* The unaltered glove design consisted of the Harbinger workout glove with attached hardware.
- *Open Flap Glove:* This design is modified with a longitudinal slit down the outside (side closest to the pinky finger), to make it easier to put on and remove.
- *Open Palm Glove:* For this design, we removed the fabric on the palm of the glove along natural seams, leaving the fingers as intact loops.

These design choices were based on the feedback we received from the first study. There were favorable comments about the Open Flap style; it had been considered easier to put on and remove than a traditional glove. The Open Palm style, based on the Velcro Finger glove, retained the desirable feature of no fabric over the palm. For this design, we removed the palm and left the remaining fingers of the glove intact, so one could simply thread the fingers through the holes, rather than Velcro them on individually. We made this change because we found that using Velcro to fasten the finger loops to the hands was cumbersome for an individual to do without assistance. These new features, as incorporated into the glove design, can be seen in Figure 32.

As in the previous study, we programmed the micro-controller to repeatedly play the vibration to "Jingle Bells" when turned on. We asked three people with SCI to test the new designs and complete a questionnaire. The participants' responses have been compiled, categorized by glove design, and are presented in Figures 29, 30, and in the text below. As in the previous glove study iteration, Figure 29 shows preferences, with green checks showing preferred features and red 'X's' indicating features which received negative reviews from participants. As in the first glove study, the small population of participants again limited our ability to draw statistical conclusions from the data, but the feedback was used to determine a final glove design based on the most highly rated features. The questionnaire can be viewed in Appendix B.

- *Unaltered Glove:* The participants agreed that this glove was easy to put on

	Easy On/Off	Sensation in Hand	Comfort
Unaltered Glove	✗	✗	✗
Open Flap Glove	✓	✗	✗
Open Palm Glove	✓✓	✓✓	✓✓

Figure 29: Comparison of glove designs from second glove field study, by feature.

and remove, and all agreed that it was not irritating to wear and only caused minimal interference with daily activities. It was noted that the heavy palm fabric made it slightly more difficult to put on than the Open Palm design, as the fingers could not be observed while it was donned. All three participants had reduced sensation in their hands, meaning they generally rely on visual cues to maintain spatial awareness of the hands and fingers. The bulkiness of the palm covering also was a concern for handling objects. The already reduced sensation was further reduced by the leather palm. On a positive note, participants did comment that the leather would be beneficial when pushing the chair with the hands and when braking, by reducing the wear on the skin of the palm. However, it was generally agreed that handling objects was a greater concern than the benefit to mobility.

- *Open Flap Glove:* Participants agreed or strongly agreed that this design was easy to put on and remove, more so than the Unaltered glove. The only irritating feature noted was the bunching of the material about the longitudinal slit on the side of the glove. When the hand was put into a fist, the material bunched into a “V” shape and caused some chafing. The same issue of the heavy leather palm fabric was noted here again, specifically that the material further reduced sensation in the hand, thus making participants less confident when handling objects.

- *Open Palm Glove:* Participants strongly agreed that this design was easy to put on and remove. The absent palm fabric made it much easier to see the fingers as they were threaded into the finger loops, allowing participants to rely on visual cues to control their fingers better during this process. The absent palm material improved confidence while handling objects. This glove design was by far the most favored of the three.

The participants wore each glove design between two and six hours, with the average being four to five hours per day. Each design was worn for two consecutive days. All participants agreed that the ideal session would last two to three hours. One participant commented that after about one hour, the glove felt as if it had “become part of the body” and the participant started “knowing” the rhythm at that point as well. The only daily activity that the vibration interfered with was talking on a phone, as it could be “heard” through the handset by the wearer (no data was reported as to whether the person on the other end of the conversation heard it). Another minor issue was that the connector between the wiring harness and hardware would detach throughout the period. Participants commented that they removed the glove for personal hygiene reasons (to wash hands and the like) and when dressing. They also stated that it would not be ideal for many of the wheelchair sports in which they engaged. There were also positive comments about the overall design, with one participant stating it “looked futuristic and less like a modified workout glove and more like a therapeutic device.”

Unaltered Glove - Most difficult to put on; could not feel fingers and they get stuck in palm - Fabric over palm heavy; limits sensation - Very snug when putting it on due to lack of give in material		
Open Flap Glove - Easy to put on, remove - Slit tends to bunch up a bit around the "V" on the side, especially when hand in a fist - Fabric over palm heavy; makes it difficult to feel objects		
Open Palm Glove - Most favored design - Open palm allowed for better sensation, and overall weight is lighter - Easy to put on, as fingers could be observed as they were threaded through finger loops		

Figure 30: Comparison chart of glove designs evaluated in second Glove Field Study.

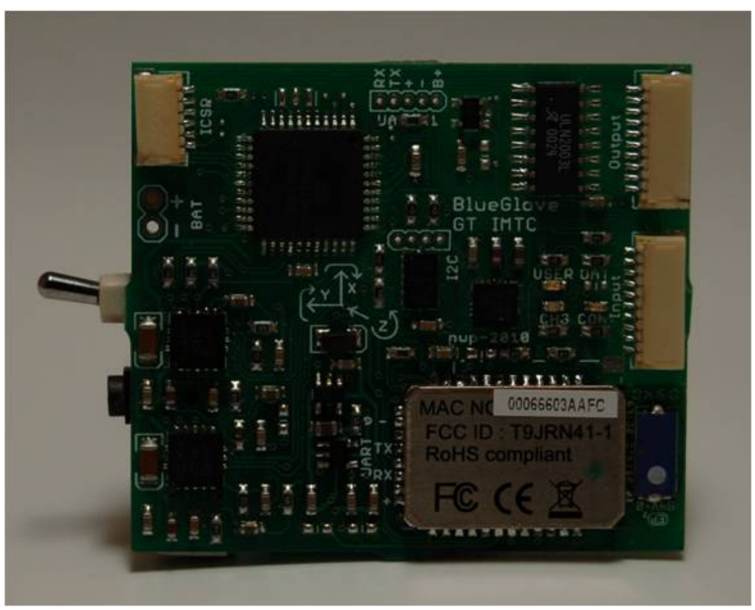


Figure 31: New hardware design used for Second Glove Study.

Figure 32: View of new features of glove: smaller, hand mounted hardware in 3D printed case, and seam-embedded, hand-sewn wiring harness.

5.3 Results

This iterative design allowed us to discover a set of desirable features for a glove worn by persons with SCI. The most favored features were:

- Harbinger style glove for the glove shell.
- Open palm for maximum sensation on the hands and improved skin-to-object contact for ease of performing daily activities.
- Small hardware mounted on the back of the hand in a 3D printed case.
- Finger loops for ease of donning.
- More robust connector between the hardware and wire harness.
- Wiring harness embedded and sewn into seams of the glove shell to minimize entanglement.
- On-board battery charging capability to avoid removing the battery from the hardware, which can be difficult for persons with limited sensation and/or motor capability of the hands.
- On/off switch.
- LEDs to indicate Bluetooth connectivity, power, and charging.

5.4 Discussion

We were surprised that the favored design in the second iteration was the Open Palm glove. It was not rated well in the first iteration (then referred to as the Velcro Finger glove). We believe this selection resulted because the new style did not incorporate Velcro to fasten the individual finger loops to the hand. One of the reasons that the Open Palm style was desirable was that it was easy to see the fingers as they were put through the finger holes. Persons with SCI often have reduced sensation in the hands, making it difficult to thread fingers through an enclosed palm area, as the fingers are no longer visible and cannot be felt. The reduced sensation of the hands also causes a lack of confidence in handling objects (such as a cup or mug); putting a glove with a thick fabric palm over a hand with reduced sensation compounded this problem. Some of our original design ideas were derived from thinking that most persons with SCI would have a nurse or family member who could help put on and remove the gloves. We quickly found that many people with SCI are very independent and even those who live with family members prefer to do these things for themselves. This discovery helped us move away from designs that relied on outside help (such as the Velcro Finger style) and toward designs that were geared for a more independent lifestyle (on-board battery charger and finger loops instead of Velcro strips). Several of the other changes we somewhat anticipated, such as the need to move away from forearm mounted hardware, and a need to encase the hardware to protect it and avoid jagged edges cutting the wearer. The comment about the connector between the hardware and the wiring harness coming detached repeatedly has led to another change; we will move back to a larger diameter ribbon cable for the wiring harness and a larger, more robust connector for the actual Passive Haptic Rehabilitation study. We also learned that an ideal session for MMT would be 2-3 hours per day.

5.5 Conclusion

This section presented the iterative glove design studies. We discovered a desirable set of features for the MMT glove that will make it most compatible for a person with SCI who has an active lifestyle. The next chapter employs this glove style to examine the concept of Passive Haptic Rehabilitation (PHR).

CHAPTER VI

PASSIVE HAPTIC REHABILITATION

The Passive Haptic Rehabilitation study, described in this chapter, provides quantitative and qualitative data about the potential of two conditions to bring about hand rehabilitation: piano playing and piano playing coupled with vibration stimulus applied to the hand. The purpose of the work in this chapter is

- *To study the extent to which each condition (piano playing, and piano playing coupled with vibration)* contributes to hand rehabilitation in persons with SCI.
- *To create an experimental design* that can be used for other studies of the same type.

6.1 Motivation

A previous pilot study performed by Kevin Huang demonstrated that using the MMT system while playing simple songs on the piano may cause some degree of hand rehabilitation in persons who have suffered a Spinal Cord Injury. However, that pilot study combined piano playing with the vibration of the MMT system, making it impossible to tell which condition (piano playing or vibration or both) caused the beneficial changes. This study seeks to isolate the rehabilitative contributions of the two conditions. We chose to use music as the vehicle for rehabilitation in our studies because of the therapeutic effect music may have on persons dealing with illness or injury. Incorporating music may serve as a motivator to ensure long-term rehabilitative exercise of the hands [62]. Music also has the ability to improve over-all sense of well-being in persons who have suffered illness or injury [77]. In addition, learning to play music provides a mental challenge and may allow the participant to learn a new skill. Our MMT system provides the added benefit of possibly making it easier to learn to play songs via PHL, as previously discussed, as well as potentially allowing the wearer to receive some additional rehabilitative improvements of the hands and fingers. Since the user does not need to use messy conductive gel, as with the electrical stimulation glove explored by Dimitrijevic [33, 34, 43, 32], the MMT system is wearable in a participant's daily life. All these factors suggest that MMT may make a convenient, at-home, mobile rehabilitation aid.

6.2 Pilot Study

6.2.1 Experiment

For this pilot study, we recruited two people who met the following criteria:

1. Males or females with C4 - T1 tetraplegia, American Spinal Injury Association (ASIA) Impairment Scale C. Persons in this range comprise our target population.

2. Must have the ability to move their individual fingers to press the keys on a musical keyboard, in order to complete the task for this study.

3. Greater than one year post-SCI. One year after injury, the liklihood of spontaneous improvement reduces in persons with SCI.

4. 18 - 75 years of age. We chose this age range to allow persons of legal majority to participate in our study. We chose the upper age limit to avoid a high confound that may be caused by changes due to advanced age.

5. Be mentally able to give consent. We required that our participants understand the study and willingly consent to be a part of our study.

6. Has enough sensory perception to feel vibration on the fingers. We needed our participants to be able to feel vibration so that they could benefit from the cueing of the vibration applied to their hands.

To ensure we captured the most accurate picture of each participant's sensation and motor function, we conducted several evaluations that are considered the standard in clinical practice for persons with SCI and are routinely used at the Shepherd Center. The participants underwent pre, mid, and post evaluations, which consisted of the following:

- *Semmes-Weinstein Monofilament Test* The Semmes Weinstein Monofilament Test is used to evaluate cutaneous sensation [2]. The test kit is composed of 20 monofilaments of different diameters. Each monofilament is mounted to the end of a plastic rod and is marked with a number and color. An image of the Semmes-Weinstein test kit is displayed in Figure 35. Each color represents a range of sensation; green is "normal," blue "diminished touch," purple "diminished protective sensation," and red indicates "loss of protective sensation" or "deep pressure sensation only" in the case of the largest diameter monofilament, numbered 6.65 [47]. Table 9 shows data for each of the monofilaments. For this study, we tested eight sites on the hand: thumb, index proximal, index distal, middle, ring, pinky proximal, pinky distal, and the palm, near the wrist, as shown in Figure 34. All sites were tested on the "palmer" side of the hand, or the inside of the hand, rather than the back or "dorsal" side of the hand. We chose these particular test sites in compliance with the standard procedure for upper extremity sensation evaluation for persons with SCI [15]. When the monofilament is pressed against the skin and bends, the amount of force that is being applied correlates (to within 5 percent of standard deviation) to the force values depicted in Table 9. For our studies, we asked the participants to close their eyes and place their right hand on the table, palm up, to evaluate sensation in the hand. The participants were told to state the finger and location (tip, base) if they felt pressure being applied. We started with the upper limit of "normal" in the green range, 2.83, applying it randomly to sites as

Table 9: Semmes Weinstein Monofilament Test

<table>
<tr><th>Monofilament</th><th>Target Force milliNewtons</th><th>Color</th><th>Hand Threshold</th></tr>
<tr><td>1.65</td><td>0.078</td><td rowspan="4">Green</td><td rowspan="4">Normal</td></tr>
<tr><td>2.36</td><td>0.196</td></tr>
<tr><td>2.44</td><td>0.392</td></tr>
<tr><td>2.83</td><td>0.686</td></tr>
<tr><td>3.22</td><td>1.569</td><td rowspan="2">Blue</td><td rowspan="2">Diminished Light Touch</td></tr>
<tr><td>3.61</td><td>3.922</td></tr>
<tr><td>3.84</td><td>5.882</td><td rowspan="4">Purple</td><td rowspan="4">Diminished Protective Sensation</td></tr>
<tr><td>4.08</td><td>9.804</td></tr>
<tr><td>4.17</td><td>13.725</td></tr>
<tr><td>4.31</td><td>19.608</td></tr>
<tr><td>4.56</td><td>39.216</td><td rowspan="10">Red</td><td rowspan="9">Loss of Protective Sensation</td></tr>
<tr><td>4.74</td><td>58.824</td></tr>
<tr><td>4.93</td><td>78.431</td></tr>
<tr><td>5.07</td><td>98.039</td></tr>
<tr><td>5.18</td><td>147.059</td></tr>
<tr><td>5.46</td><td>254.902</td></tr>
<tr><td>5.88</td><td>588.235</td></tr>
<tr><td>6.1</td><td>980.392</td></tr>
<tr><td>6.45</td><td>1764.706</td></tr>
<tr><td>6.65</td><td>2941.176</td><td>Deep Pressure Sensation Only</td></tr>
</table>

indicated in Figure 34. We then "bracketed" until we found the smallest diameter monofilment that the participant could feel for each test site, which was the value recorded. Each time, the monofilament was applied with just enough force to note a bend and held for 1.5 seconds or until the participant indicated the location of the sensation (test site on the hand). Semmes-Weinstein data may be analyzed in its raw numerical form, or it may be scaled by color coded sensation ability: green (normal, minimum monofilament code 2.83 = 0), blue (diminished light touch, minimum monofilament code 3.61 = 1), purple (diminished protective sensation, minimum monofilament code 4.31 = 2), red (loss of protective sensation, minimum monofilament code 6.65 = 3) and red (unable to feel largest monofilament = 4) [97, 102].

- *Grasp and Release Test (GRT)* The Grasp and Release Test was originally designed as a way to assess hand function in persons with tetraplegia due to spinal cord injury. It was specifically geared toward evaluating hand function in those who had C5 or C6 level injury. The GRT consists of six activities that simulate typical grasps that a person might perform in daily life and are often needed to complete activities of daily living (ADL). The manipulated objects include pegs, a paperweight, a fork, blocks, a can and a tape. Three of the activities evaluate the lateral grasp (peg, fork, and tape) and three the palmer grasp (paperweight, block, and can). The evaluation is performed by first describing each of the various tasks and then providing an opportunity for the participant to try each activity in a pre-test period. Once the evaluator is satisfied with the participant's understanding of the activity and his ability to perform it, the actual graded evaluation is administered, this time in a different sequence than the pre-test so as to avoid the effect of fatigue. The performance is scored by the number of correctly completed iterations in a 30 second period. We also annotate incorrectly performed iterations and record the type of error made with a failure code (force, position, control, and other) [75, 91, 48]. An example score sheet can be found in Appendix H.

- *Action Research Arm Test (ARAT)* The Action Research Arm Test was originally designed to be a simple, repeatable and sensitive evaluation of the upper extremity "motor status" in persons who had suffered injury to the brain, specifically stroke [61, 101, 70]. The ARAT is a 57-point evaluation that is sub-divided into four sub-scales: grasp, grip, pinch, and gross movement. Each sub-scale consists of several activities. Unlike the GRT, each activity is attempted only once and must be completed within a given time frame. A score of three is given if the action is completed correctly within five seconds. A two is assessed if the action is generally completed correctly and takes longer than five seconds but less than sixty seconds to complete. A one is given if the participant is partially successful in completing the activity, and a zero if they fail to complete or even attempt the action. The grasp sub-scale consists of six activities. The participant must pick up each object and place it on the shelf. The objects consist of 10cm^3, 2.5cm^3, 5cm^3, and 7.5cm^3 wooden blocks, a cricket ball, and a sharpening stone. The grip sub-scale has the participant pour water from one glass to another, displace a 2.25cm and a 1cm alloy tube from one peg to another, and place a washer over a bolt. The pinch sub-scale tasks the participant with picking up either a ball bearing or marble, raising it to a shelf and depositing it in a tray. The six activities in this sub-scale are picking up the ball bearing between the ring finger and thumb, the middle and thumb, the index and thumb, and the marble between the index and thumb, ring and thumb and the middle and thumb. The gross movement sub-scale has the participant start with hands in the lap. The participant is then asked to put the hand first behind the head, then to the top of the head, and finally to the mouth. These must be done without undue motion of the head (such as bending the neck to place the head closer to the hand). A sample score sheet may be found in Appendix I. The ARAT procedure, as originally described, has the evaluator stop at the first test in each sub-scale if the participant fails to complete the activity, assuming the participant will fail to complete any other tests in that sub-scale. However, due to the variability of recovery in people with SCI, there is the possibility that a participant may successfully complete a subsequent test in a sub-scale, even after the failure of the first test in the sub-scale. In this study, we performed the ARAT in the way commonly performed at the Shepherd Center with persons with SCI [15]. An image of an ARAT test kit can be seen in Figure 33 [5]. A 10% change has been given as the "Minimal Clinically Important Difference (MCID)" for the ARAT, which

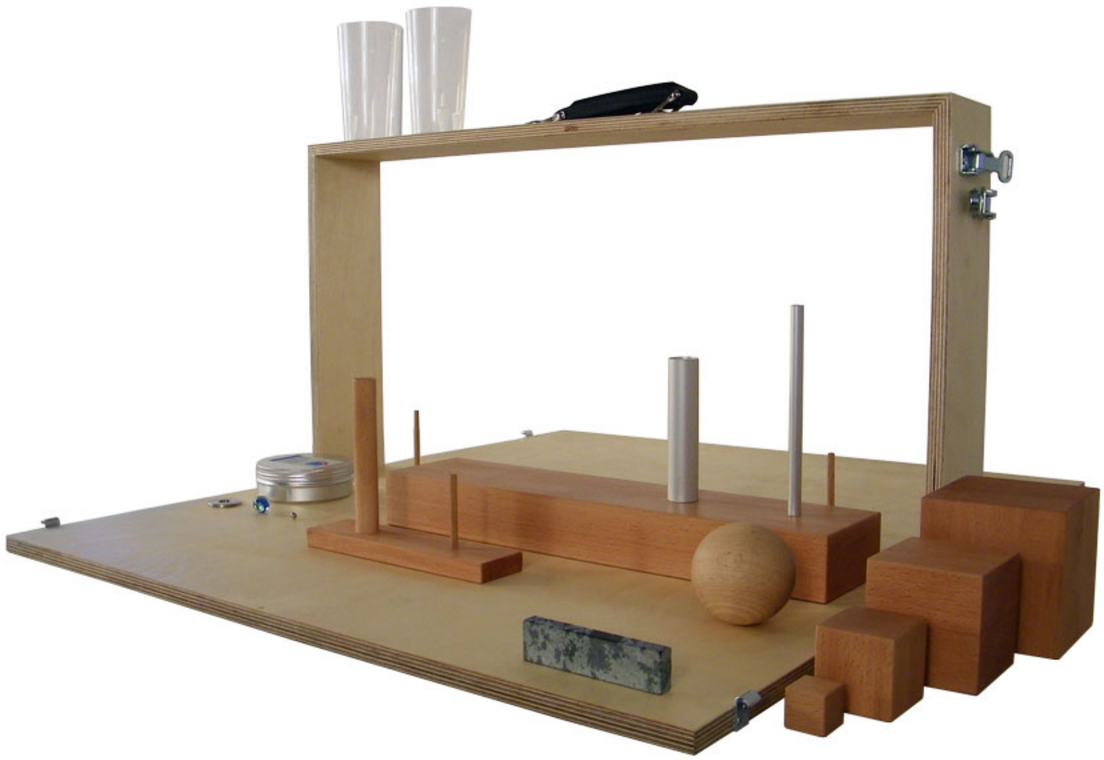


Figure 33: Action Research Arm Test kit

represents a change of 5.7 points overall [92].

The participants were also asked to complete pre-study questionnaires, as listed below:

- *Handedness Survey* The Edinburgh Inventory of Handedness survey can be found in Appendix F. The handedness survey assesses the participant's preferred hand for various activities, such as eating and writing [78].

- *Capabilities of Upper Extremity Instrument (CUE)* The Capabilities of Upper Extremity (CUE) instrument was designed as a survey to try to quantify a participant's ability to perform skills that enable proper execution of tasks of daily living [67]. Each participant was asked a series of questions (see Appendix K for the list of questions) and given a Likert scale from 1 to 7 on how much difficulty he or she has performing the various described tasks. The self-reported abilities enumerated on the CUE helped capture meaningful changes in a participant's abilities that might not otherwise be measured or observed.

- *Musical Ability Questionnaire* We wanted to discover what formal musical background our participants may have in order to consider if formal music instruction may have an impact on performance. Unlike the PHL study, we did not use formal musical background as a way to screen possible participants, as the injured population was extremely small. For the PHR study, we chose to focus on the potential rehabilitation benefits of the MMT system. The pre questionnaire is located in Appendix G.

The participants were asked to complete post-study questionnaires, as annotated below:

- *Capabilities of Upper Extremity Instrument (CUE)*

- *Post-Study Questionnaire* We devised a questionnaire in order to determine participants' perceptions and opinions regarding several aspects of this study. We wanted to determine if participants enjoyed playing the piano, if they believed their hands had improved in any way, and whether or not they felt their mood had improved over the course of the study. We also asked glove-specific questions. The glove-specific questions addressed comfort and social acceptability, the impact (if any) of the vibration on daily activities, and perception about how the glove may have aided in the ability to learn to play the songs. The questionnaire can be found in Appendix M.

For the pilot study, the participants performed the most demanding of the possible two conditions, piano playing coupled with vibration cues delivered using the MMT system. We created this study in order to evaluate song selection, to evaluate the ability of the participants to play songs of varied length and difficulty, and to check the correct function and robustness of hardware and software.

The two participants of the pilot study came to the Shepherd Center three times a week to play the piano for 30 minutes each session, over a period of eight weeks. Both participants took home a MMT glove that had the song they were working on that week programmed into the glove. When the participant turned on the glove it repeatedly played the song in vibration form only with a one minute break between each repetition. Participants were asked to wear the glove for at least two hours a day for at least five days during the week. In order to help assure compliance with this request, the hardware also contained accelerometers and a mini SD card to record accelerometer data and time, allowing us to see that the glove was worn for the correct length of time and not sitting stationary. The songs were "pentatonic" meaning that they stay on the same five keys of the piano with minimal lateral movement. Most songs had an almost one-to-one mapping of fingers to specific keys. During the first session per week, the participants rehearsed the new song, which was broken into smaller phrases for ease of learning. At the start of the subsequent sessions during the week, we evaluated their ability to play the songs they were learning using a MIDI capture keyboard and the Dynamic Time Warping Algorithm used in the Passive Haptic Learning study discussed in the previous chapter. The participants were asked to attempt to play the song they had been learning after one exposure to the song at the start of the session.

For this study, we wanted to use actual songs in order to help motivate the participants to want to learn the songs and make the activity more rewarding. With the guidance of Dr. Tom Scott, a composer and director with a PhD in music, we found eight pentatonic songs in "Sing it Yourself: 220 Pentatonic American Folk Songs" [20]. The initial eight songs are shown in Appendix L.

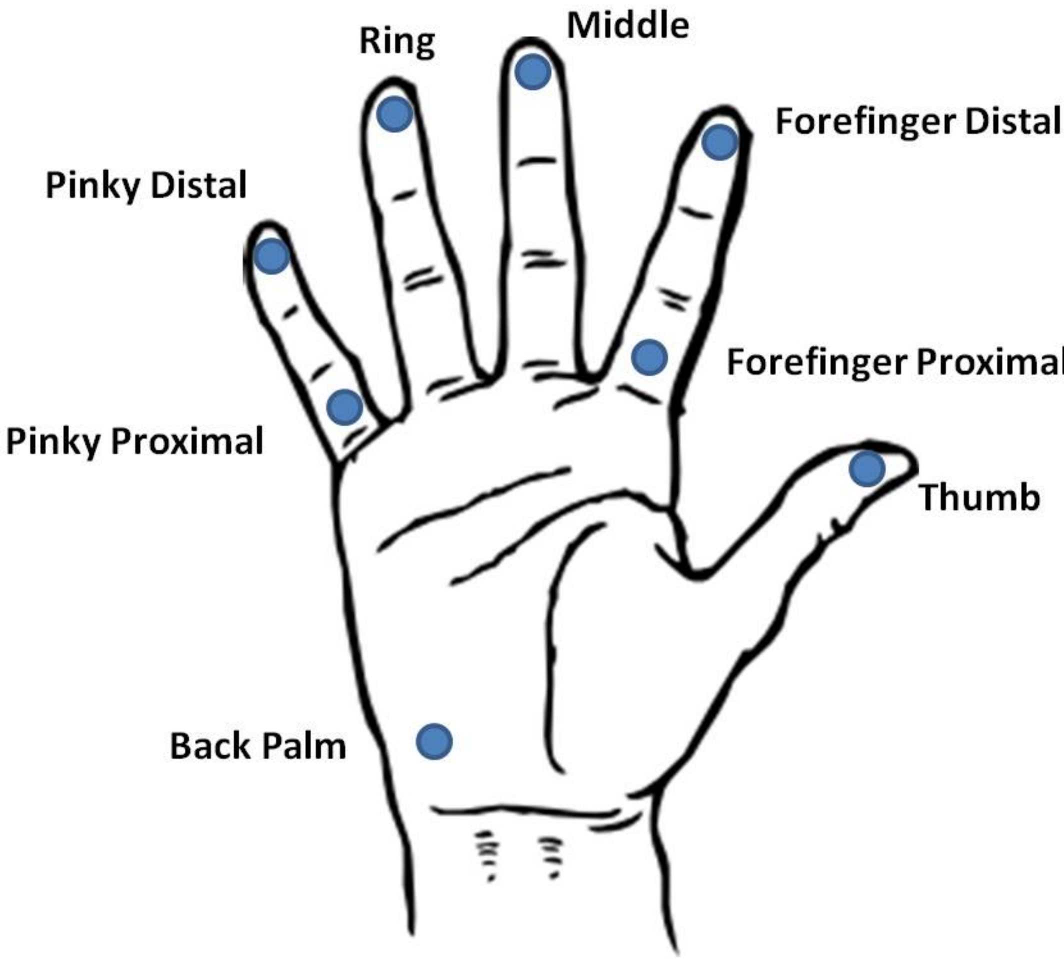


Figure 34: Semmes Weinstein Test Sites, Right Hand, Ventral View

Figure 35: Semmes Weinstein Test Kit Image

Table 10: Participant Demographics.

Participant Number	Date of Injury	Level of Injury	AIS	Age	Sex
1	3 MAR 2003	C8	D	45	Male
2	24 SEP 2006	C5	D	75	Male

Table 11: Pilot Data: Participant 1, Semmes Weinstein

Site	Pre	Mid	Post	Change
Thumb	2.83	2.36	2.36	-0.47
Forefinger Prox.	2.83	2.83	2.36	-0.47
Forefinger Dist.	2.36	1.65	1.65	-0.71
Middle	2.83	2.36	2.36	-0.47
Ring	2.44	2.36	1.65	-0.79
Pinky Prox.	3.61	2.83	1.65	-1.96
Pinky Dist.	2.83	1.65	1.65	-1.18
Back Palm	3.61	3.84	2.36	-1.25
Average	2.92	2.49	2.01	-0.913

6.2.2 Results

Table 10 provides injury data about our participants. Tables 11 and 14 show the Semmes Weinstein data for participants 1 and 2, respectively. Both participants had improvements in their sensation, as indicated by the reduction in the diameter sizes of monofilaments each was able to perceive. Participant 1 had an average reduction

Table 12: Pilot Data: Participant 1, Grasp and Release Test (GRT)

	Pre			Mid			Post			δ
Event	Att.	Err	Score	Att.	Err	Score	Att.	Err	Score	
Fork	44	0	44	41	0	41	38	0	38	-6
Can	27	4	23	31	0	30	21	2	19	-4
Tape	22	2	20	25	2	23	25	1	24	+4
Block	40	1	39	39	1	38	43	1	42	+3
Peg	34	0	34	33	0	33	35	0	35	+1
Totals			160			165			158	-2

Table 13: Pilot Data: Participant 1, Action Research Arm Test (ARAT)

	Pre	Mid	Post	Change
Totals	49	50	50	+1

Table 14: Pilot Data: Participant 2, Semmes Weinstein

Site	Pre	Mid	Post	Change
Thumb	4.31	4.17	4.17	-0.14
Forefinger Prox.	3.84	4.17	4.31	+0.47
Forefinger Dist.	4.31	4.31	4.56	+0.25
Middle	4.17	3.84	4.08	-0.09
Ring	3.84	3.61	3.61	-0.23
Pinky Prox.	4.17	4.74	4.08	-0.09
Pinky Dist.	3.84	4.17	3.61	-0.23
Back Palm	4.31	4.31	3.84	-0.47
Average	4.09	4.17	4.03	-0.066

Table 15: Pilot Data: Participant 2, Grasp and Release Test (GRT)

	Pre			Mid			Post			δ
Event	Att.	Err	Score	Att.	Err	Score	Att.	Err	Score	
Fork	21	1	20	20	0	20	17	1	16	-4
Can	18	0	18	18	2	16	16	0	16	-2
Tape	14	0	14	12	1	11	12	1	11	-3
Block	25	0	25	28	0	28	26	0	26	+1
Peg	24	0	24	22	3	19	21	3	18	-6
Totals			101			94			87	-14

Table 16: Pilot Data: Participant 2, Action Research Arm Test (ARAT)

	Pre	Mid	Post	Change
Totals	39	40	45	+6

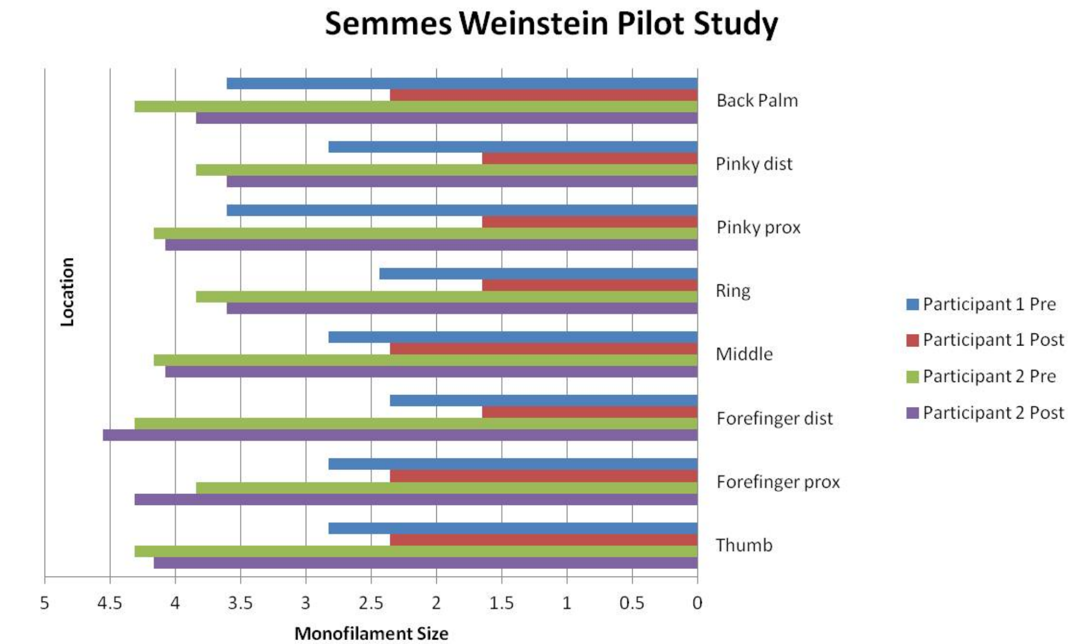


Figure 36: Pilot Study Semmes Weinstein Data, two participants

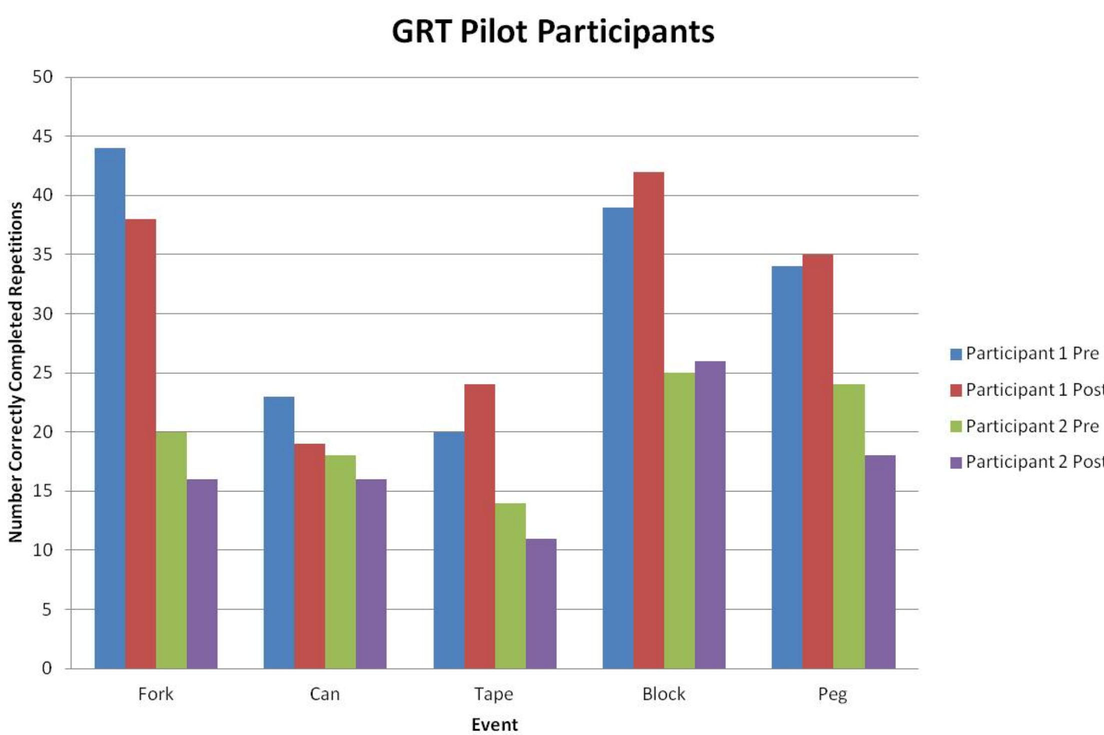


Figure 37: Pilot Study Grasp and Release Data, two participants

of -0.913 mm, and participant 2 saw a reduction of -0.066 mm. When evaluating a participant with the Semmes-Weinstein, a reduction is a positive sign in terms of sensation. A decrease on the Semmes-Weinstein indicates that the participant was able to feel a monofilament of smaller diameter, demonstrating a possible improvement in the ability to feel very slight sensation. Grasp and Release Test data for the participants showed a reduction in the number of correctly completed iterations of the six test activities. Tables 12 and 15 show GRT data for participants 1 and 2, respectively. ARAT data is summarized for participant 1 in Table 13 and participant 2 in Table 16. Participant 1 did not experience a significant change in overall ARAT score, with a pre total of 49, post of 50. However, participant 2 had an increase of 6, with a pre score of 39, post of 45, and with most increase in the pinch sub-scale.

6.2.3 Discussion

Both pilot participants saw an improvement in their sensation as indicated by the reduction in monofilament diameter they were able to perceive. Both saw a decrease in the number of correctly completed repetitions on the GRT. We had expected to observe an increase in number of correctly performed repetitions on the GRT, but we believe that further study with more paticipants is necessary. We were very intrigued by the improvements in sensation indicated by the Semmes-Weinstein. Considering the ARAT data, we observed that participant 1 only had a one-point improvement, but we saw that participant 2 demonstrated an increase of overall ARAT score of 6 points. As stated earlier, an improvement of at least 10% is considered the "Minimal clinically important difference (MCID)" for the ARAT [92]. While the improvements on the Semmes-Weinstein for Participant 2 were small, we did observe positive change. Generally, such improvements are not expected in persons greater than one year post-SCI. These pilot study results suggested that our mechanism, vibration, may have been providing some degree of rehabilitative change, but further study was needed. We hypothesized that the vibration may be causing improvements in sensation. Sensation levels that move closer to "normal" may aid in the performance of tasks requiring fine motor skill. The ability to handle objects may be tied to an ability to receive and process sensory data about the object being manipulated. The changes we observed in this pilot study, especially when looking at participants' improvements in sensation, are not "typical" in persons who are greater than one year post-injury and who do not participate in therapeutic activities. Many people who have suffered SCI do not receive upper extremity rehabilitation after the one year post-injury mark due to the belief that there are not gains to be made after that point. Researchers in upper extremity rehabilitation for persons with SCI are working to show that there is potential for changes that may result in quality of life improvements. We hope to demonstrate upper extremity improvements which may lead to greater independence and quality of life. Ideally, we seek an interesting, relatively inexpensive system that can be used at home that provides a form of rehabilitation that participants will enjoy doing. Our pilot study results indicate that MMT has this potential, but we must conduct a larger-scale study. For the pilot study, we had both participants use the glove to see if any interesting changes took place at all. Since we observed some interesting results, we now seek to compare the use of vibration stimuli (provided by the MMT system) coupled with an active rehabilitation activity (piano playing) with just the active rehabilitation activity (piano playing). Such a study may show if there is any advantage to using the MMT system over performing active rehabilitation alone.

6.3 Full Study

6.3.1 Experiment

For this study, we recruited ten "hands." In this case, we had seven participants. Three of them qualified on both the left and right hand and were offered the opportunity to complete the study with each hand at separate times. Each participant had to meet the following inclusion criteria:

1. Males or females with C4 - T1 tetraplegia
2. Must have the ability to move their individual fingers to press the keys on a musical keyboard.
3. Greater than 1 year post-SCI.
4. 18 - 75 years of age.
5. Be mentally able to give consent.
6. Has enough sensory perception to feel vibration on the fingers.
7. Must demonstrate manual muscle test grade greater than 2 in each of the following, but not to total more than 10: wrist extension, flexor profundis (middle finger), and abductor minimi (pinky finger)

The population of persons with SCI who are able to meet the inclusion criteria from the pilot made it possible to have a wide variety of ability levels within our study group. In order to ensure a more homogeneous group, we added the requirement for participants to meet the manual muscle test requirements listed above. If a participant was too strong, he would not have the potential to show measurable improvement. Conversely, if a participant was too weak, he might be unable to activate the piano keys with his fingers, making him unable to play the songs. We also added the 2-Point Discrimination Test and a measure of coordination and strength. We measured strength and coordination using a new device called the AMES (AMES Technology Inc, Oregon), while the 2-Point Discrimination Test adds another assessment of finger sensation. The 2-Point Discrimination Test specifically determines the ability to sense two distinct points of varying differences in separation (measured in mm).

The participants of the full study came to the Shepherd Center three times a week to play the piano for 30 minutes each session, over a period of eight weeks. The apparatus for an active practice session is shown in Figure 38. *Without glove* participants had no additional requirements beyond just playing piano during the in-lab sessions. *With glove* participants took home an MMT glove that had the song they were working on that week programmed into the glove so that it played the song, in vibration form only, while it was turned on, with a one minute break in between each repetition of the song. They were asked to wear the glove for at least two hours a day for at least five days during the week. In order to help assure compliance with this request, the hardware also contained accelerometers and a mini SD card to record accelerometer data and time, allowing us to see that the glove was worn for the correct length of time and not sitting stationary. As in the pilot study, the songs were "pentatonic," and most songs had an almost 1:1 mapping of fingers to specific keys. During the first session per week, the participants rehearsed the new song, which was broken into smaller phrases for ease of learning. At the start of the subsequent sessions during the week, we evaluated their ability to play the songs they were learning using a MIDI capture keyboard and the Dynamic Time Warping Algorithm used in the Passive Haptic Learning study discussed in the previous chapter. To accomplish this, they were asked to attempt to play the song they had been learning after one exposure to the song at the start of the session. Specifically, we played the song practiced in the previous session once on the piano, lighting the keys as each note was played. The participants then attempted to play the song themselves, and we calculated the error metrics from the captured performance.

Because of the small population of qualified persons for this study, if a participant qualified with both hands, we offered him the opportunity to complete the study first with one hand and then the other. We did need to consider the possibility of a learning effect taking place when an individual performs a similar task twice, because

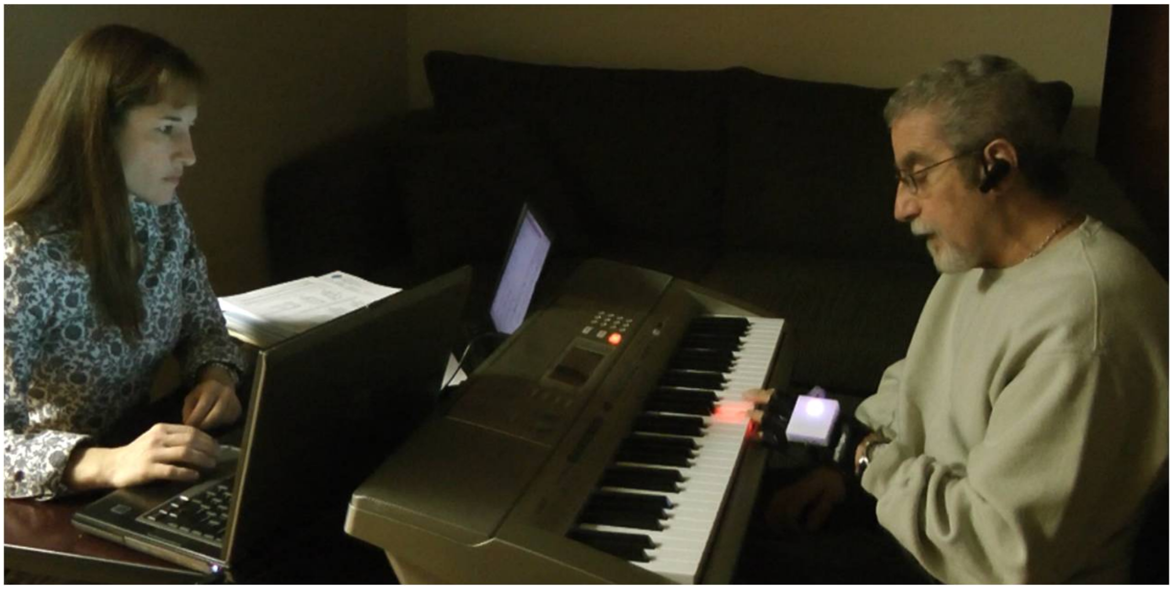


Figure 38: Active Practice Session

in this particular study, we were more concerned with the potential rehabilitative benefits that may result, rather than possible learning. In order to accommodate the possibility of a participant going through the study multiple times with each hand, or from one condition (*without glove*) to the other (*with glove*), we had to add songs to the list. We selected and processed an additional 16 songs, giving us a total of 24 from which to choose. The additional 16 songs are presented in Appendix P. We could not guarantee at the start that we could recruit a given number of participants, so we chose to flip a coin to determine the condition the first participant would undergo (*with* or *without glove*) and then do the opposite for each subsequently recruited participant. Those who started in the *without glove* condition were given the opportunity to then go through the study with the glove to ensure they had the same possible benefit from the MMT system, in case it should it provide a rehabilitative advantage over just playing the piano alone. We recruited seven participants. Their demographics are listed in Table 17.

The participants underwent pre, mid, and post evaluations, which consisted of:

- *Semmes Weinstein Monofilament Test* previously discussed in subsection 6.2.1

Figure 39: Touch Test Two-Point Discrimination.

above.

- *Two Point Discrimination Test* The two-point discrimination test is used to help determine cutaneous sensitivity. The device we used is a plastic wheel that has a single point, as well as the ability to vary the distance between two points from 2mm up to 15mm in separation (Touch Test). "Normal" sensation is considered to be anything below 10mm in separation between the points [72], although 6mm has also been cited as the upper limit for "normal" sensation [100, 11]. The participant is asked to close her eyes and state if she feels one point or two and the name of the finger being touched. The value we recorded was the smallest separation the participant was able to distinguish. The single point on the wheel was employed throughout the exam as a control. The two-point discrimination test device is depicted in Figure 39 [9].

- *Grasp and Release Test (GRT).* As described above.

- *Action Research Arm Test (ARAT).* As described above.

- *Test of Strength and Coordination* The Assisted Movement with Enhanced Sensation (AMES) device (AMES Technology, Inc, Portland, OR) is a robotic therapy system that was designed to explore the application of vibration to the antagonistic (opposite) muscle being used in an activity to aid in motion [15, 28]. The AMES device is not only used for therapy, but also provides a novel method of evaluation of hand and wrist strength and coordination in fine motor activities. For this study, we only employed the AMES as a way to evaluate the upper extremity of participants. To accomplish this task, the participant was seated next to the device, with hand and arm to be evaluated seated in the device. The AMES was properly adjusted to accommodate the anthropometrics of the participant prior to the evaluation. The first activity was a calibration, which moved the participant's hand and wrist through a series of passive motions. During the grasp strength test, the participant was asked to open the hand (thumb and fingers going away from each other in a "V" shape) to maximum extension three times. The same was done for flexion, this time the participant was asked to make a best attempt to close the hand (thumb and fingers brought together) over three attempts. The participant's highest score was always displayed (even from past sessions) as a measure of progress. After these trials, the participant then opened and closed the hand in a controlled fashion, causing a cursor on the screen to move up (when the hand was extended) or down (when hand flexed). The participant was instructed to attempt to track the two pylons on the screen that would move at precise intervals up or down. A score was assigned based on the amount of time the participant was able to keep the cursor between the pylons. The wrist strength test was then accomplished by having the participant make three attempts to flex the wrist (move the palmer side inward, toward the body), as best they could. The participant then made three best attempts at extension of the wrist (moving outward from the body). The tracking task was then performed, this time, keeping a cursor between pylons in a horizontal axis; pulling the wrist inward to move the cursor in one direction, extending outward to move the opposite direction. Again the score was accumulated based on the amount of time the participant kept the cursor between the pylons [28]. The AMES evaluation sheet we used for this study is available in Appendix J.

The participants were also asked to complete pre-study questionnaires, as listed below:

- *Handedness Survey.* As described above.
- *Capabilities of Upper Extremity Instrument (CUE) [67].* As described above.
- *Musical Ability Questionnaire.* As described above.

The participants were asked to complete post-study questionnaires, as annotated below:

- *Capabilities of Upper Extremity Instrument (CUE)*
- *Post-Study Questionnaire* In the pilot study, both participants used the glove. For the full study, we needed to create another post questionnaire that would capture the experiences of participants who didn't use the glove as well as those who did. This method would allow us to compare the perceptions of both conditions. We built upon the questions that we had devised for the pilot study and discarded glove specific questions. The *without glove* post questionnaire is featured in Appendix N, and the *with glove* group questionnaire is in Appendix O.

6.3.2 Results

The demographics of our study "hands" are shown in Table 17.

6.3.2.1 Semmes-Weinstein

Using the paired t-test, we found that the overall average (all testing sites) pre to post differences in Semmes-Weinstein measurement for the hands of people in the *with glove* population was reduced a statistically significant amount ($SWmean_{with} =$

Table 17: Full Study Participant Demographics.

Hand	Injury Date	Level	AIS	Age	Sex	Hand	Glove
1	31 MAR 2008	C6	C	58	M	Right	Without
2	18 JUL 2010	C5	D	70	F	Right	Without
3	18 MAY 2010	C3/C7	C	34	M	Right	Without
4	25 MAY 2004	C5/C6	B	26	M	Left	Without
5	10 AUG 2009	C5	D	24	M	Right	Without
6	16 APR 2009	C3/C6	D	41	M	Right	With
7	24 NOV 2009	C6/C7	A	29	M	Right	With
8	25 MAY 2004	C5/C6	B	26	M	Right	With
9	18 JUL 2010	C5	D	70	F	Left	With
10	31 MAR 2008	C6	C	58	M	Left	With

Table 18: Full Study Semmes-Weinstein Data

Without Glove				*With Glove*			
Hand	Pre	Post	Diff.	Hand	Pre	Post	Diff.
1 Rt	4.38000	4.38125	0.00125	6 Rt	4.24625	4.13500	-0.11125
2 Rt	4.34625	4.16500	-0.18125	7 Rt	3.89375	3.68000	-0.21375
3 Rt	2.78125	2.87875	0.0975	8 Rt	3.31250	3.11250	-0.20000
4 Lt	2.90750	2.81000	-0.09750	9 Lt	4.37750	3.85375	-0.52375
5 Rt	2.47875	2.58625	0.1075	10 Lt	4.58875	3.98125	-0.60750
Averages	3.37875	3.36425	-0.0145	Averages	4.08375	3.75250	-0.33125

-0.33) versus the *without glove* population ($SWmean_{without}$ = -0.015), p = 0.01, 95% confidence interval is 0.058 to 0.578, Cohen's d: 1.78, indicating a very high effect [25]. In this case, a reduction demonstrates an improvement in hand sensitivity, as it means the participant was able to feel a smaller diameter monofilament. Semmes-Weinstein data are shown in Table 18 and Figure 40.

We also graphically depict the changes from pre to post for the five *without glove* participants in Figure 41, and the five *with glove* participants in Figure 42 for the between subject study.

In the hand graphics shown, green indicates an improvement in sensation with corresponding reduction in monofilament diameter, while red means reduction in

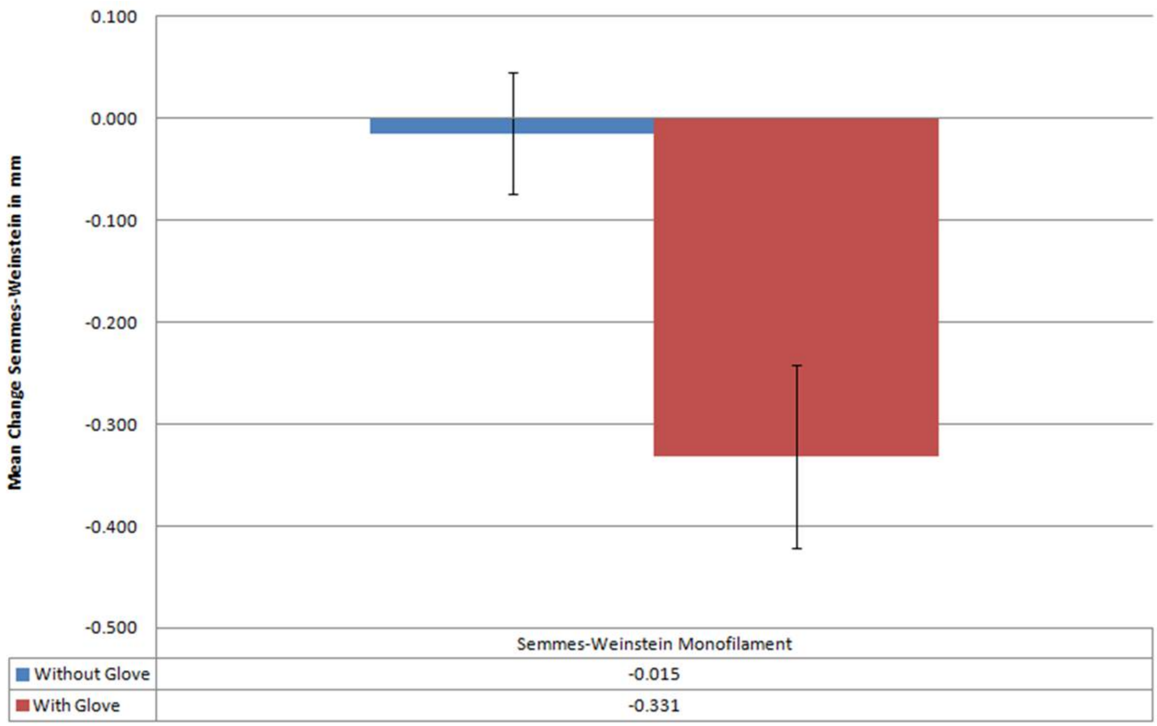


Figure 40: Graphical depiction of Semmes-Weinstein results by condition.

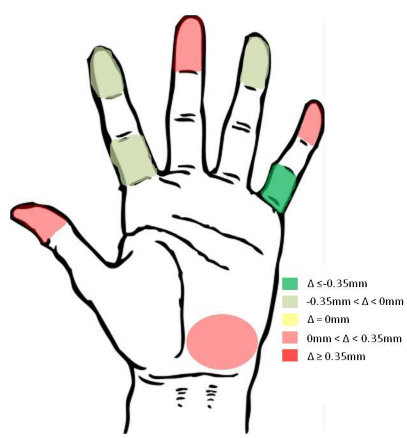


Figure 41: Change on Semmes-Weinstein pre to post *without glove* condition.

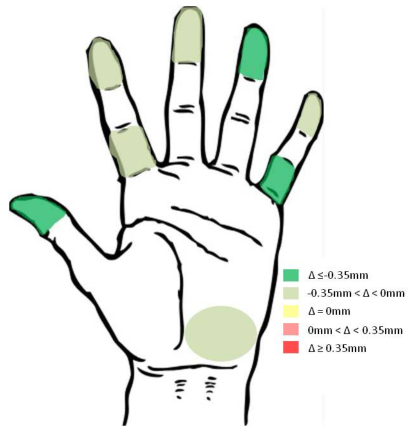


Figure 42: Change on Semmes-Weinstein pre to post *with glove* condition.

sensation with higher diameter monofilament. Yellow indicates no change. We also display the Semmes-Weinstein data with an arrow chart, indicating pre and post values to help illustrate the changes as the participants approach the goal of "Normal" on the chart. The *without glove* group arrow chart is shown in Figure 43 and the *with glove* group in Figure 44.

We observed several participants make transitions from one category of sensation to another (for example, from "Diminished Light Touch" to "Normal.") We have displayed these results graphically using the Semmes-Weinstein color coding for the *without glove* group in Appendix Q and for the *with glove* group in Appendix R.

6.3.2.2 2-point Discrimination Test

The 2-point discrimination test also failed to achieve statistically signicant change. The means of the two groups were $2PTmean_{with}$ = -2.36 for the *with glove* population and $2PTmean_{without}$ = -0.6 for the *without glove* population (p = 0.15) (see Table 19).

In this case, a reduction indicates the ability to distinguish between two points that are closer together. The 2-point discrimination test results are graphically depicted for the *without glove* group in Figure 45 and the *with glove* group in Figure 46. In the figures, green indicates an improvement in perception, yellow is no change, and

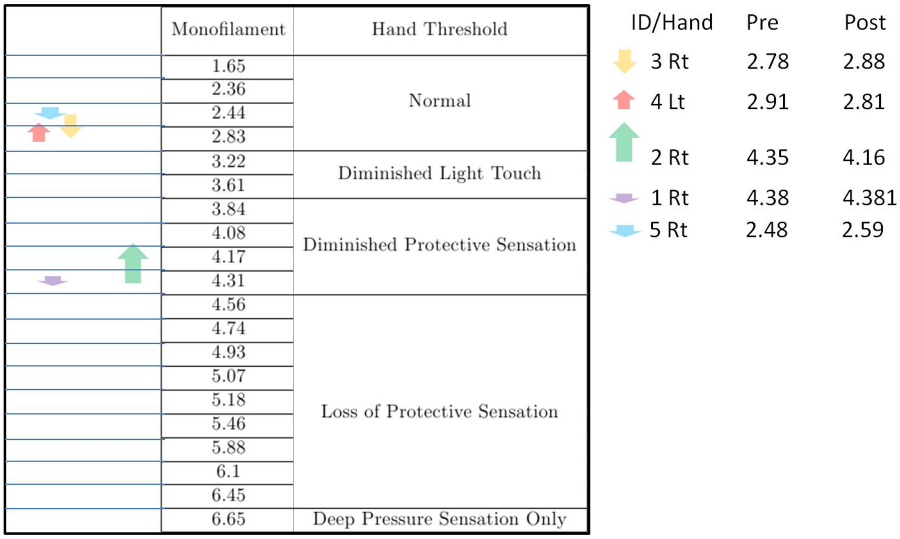


Figure 43: Change on Semmes-Weinstein arrow chart *without glove* condition.

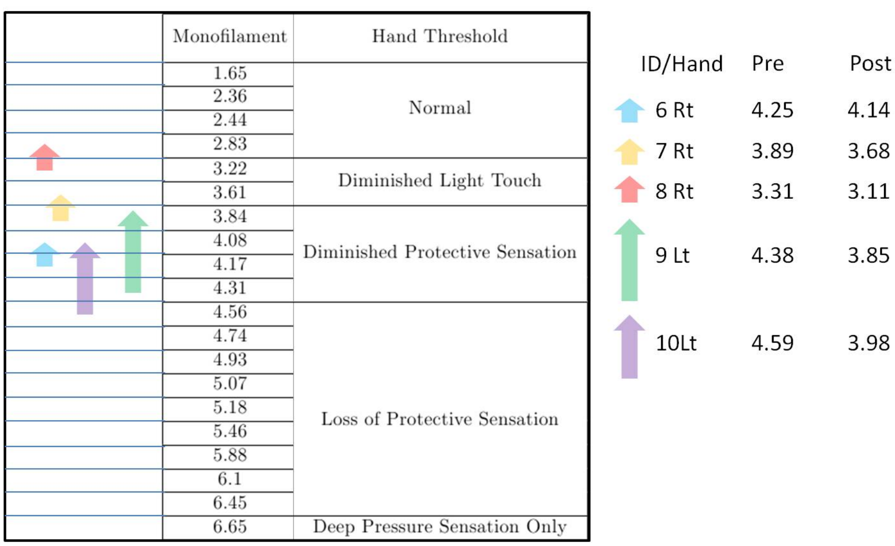


Figure 44: Change on Semmes-Weinstein arrow chart *with glove* condition.

Table 19: Two-Point Discrimination Test Data

Without Glove				*With Glove*			
Hand	Pre	Post	Diff.	Hand	Pre	Post	Diff.
1 Rt	6.4	7.0	0.6	6 Rt	4.4	3.4	-1.0
2 Rt	12.6	11	-1.6	7 Rt	11.6	4.2	-7.4
3 Rt	3.0	3.2	0.2	8 Rt	6.6	2.6	-4.0
4 Lt	5.8	3.6	-2.2	9 Lt	13.2	14.0	0.8
5 Rt	3.2	3.2	0	10 Lt	10.6	10.4	-0.2
Averages	6.2	5.6	-0.6	Averages	9.28	6.92	-2.36

red shows a reduction in perception of the two points.

6.3.2.3 Test of Strength and Coordination

Strength and coordination data from the AMES device showed that the participants did not demonstrate any significant change in wrist or hand strength over the course of the study. Results of the AMES strength tests are shown in Tables 20 and 21. AMES joint position tests are displayed in Tables 22 and 23.

6.3.2.4 Grasp and Release Test

Glove group participants also showed greater improvement on the GRT ($GRTmean_{with}$ = 29) versus the *without glove* population ($GRTmean_{without}$ = 15), p = 0.02, 95% confidence interval of 0.5 through 27.5, Cohen's d: 1.55, indicating a very high effect [25]. GRT data are shown in Table 24 and Figure 47. In the case of the GRT, an increase represents an overall increase in the number of correctly completed repetitions of a given activity in the test. Thus, a positive change in value is considered desirable in this test.

6.3.2.5 Action Research Arm Test

We did observe a positive trend in the ARAT scores, particularly in the case of the pinch sub-scale. However, the means did not show a statistically significant difference. In the case of our participant population, we had several who performed at or near the

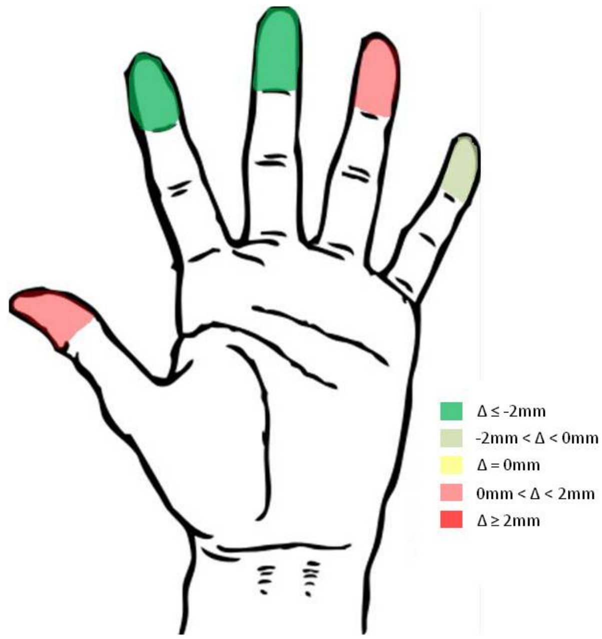


Figure 45: Graphical depiction of 2-point discriminator test results *without glove*.

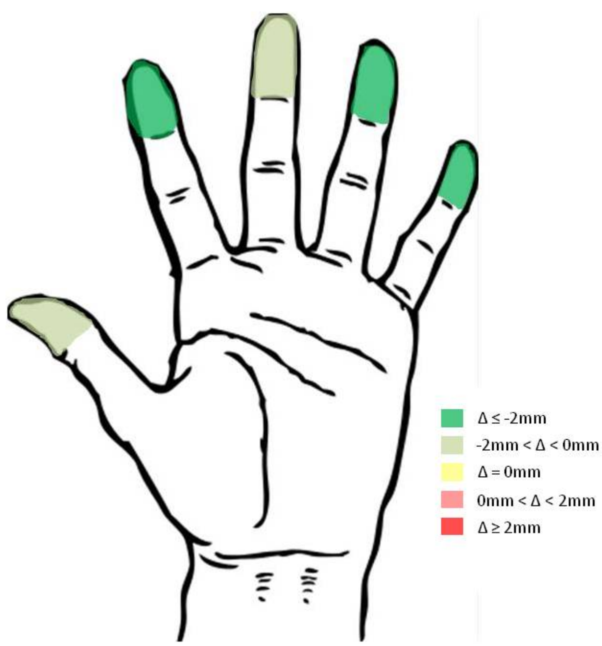


Figure 46: Graphical depiction of 2-point discriminator test results *with glove*.

Table 20: Full Study AMES Strength Data *Without Glove*

	Grasp Strength						Wrist Strength					
	Extension			Flexion			Right			Left		
Hand	Pre	Post	Diff.	Pre	Post	Diff.	Pre	Post	Diff.	Pre	Post	Diff.
1 Rt	13	14.8	1.8	27.67	33	5.33	39.67	51.57	11.9	53	95	42
2 Rt	8.77	10.57	1.8	29.47	26.63	-2.83	31.47	31.8	0.33	54.87	43.1	-11.77
3 Rt	3.73	2.27	-1.47	35.67	32.37	-3.3	10.93	18.57	7.63	34.6	44.07	9.47
4 Lt	7.93	13.63	5.7	7.6	15.23	7.63	137.5	154.53	17.03	101.33	111.43	10.1
5 Rt	-1.73	0.63	2.37	33.63	34.07	0.43	30.07	62.77	32.7	42.8	52.17	9.37

Table 21: Full Study AMES Strength Data *With Glove*

	Grasp Strength						Wrist Strength					
	Extension			Flexion			Right			Left		
Hand	Pre	Post	Diff.	Pre	Post	Diff.	Pre	Post	Diff.	Pre	Post	Diff.
6 Rt	16.33	20.47	4.13	35.67	37.5	1.83	60.33	82.8	22.47	70	96	26
7 Rt	4.33	3.33	-1	13.33	15.77	2.43	-0.67	30.5	31.17	57.33	68.97	11.63
8 Rt	0.27	0.57	0.3	0.17	10.37	10.2	60.67	87.77	27.1	46.83	79.77	32.93
9 Lt	7.2	9.27	2.07	15.93	15.33	-0.6	46.4	41.2	-5.2	18.97	14.57	-4.4
10 Lt	14.63	14.7	0.07	44.17	40.67	-3.5	85.9	113.23	27.33	47.57	62.17	14.6

Table 22: Full Study AMES Joint Position Data *Without Glove*

	Grasp Joint Pos			Wrist Joint Position		
Hand	Pre	Post	Diff.	Pre	Post	Diff.
1 Rt	294	398	104	494	421	-73
2 Rt	159	386	227	405	321	-84
3 Rt	105	90	-15	307	447	140
4 Lt	271	545	274	401	590	189
5 Rt	137	103	-34	421	557	136

Table 23: Full Study AMES Joint Position Data *With Glove*

	Grasp Joint Pos			Wrist Joint Position		
Hand	Pre	Post	Diff.	Pre	Post	Diff.
6 Rt	524	597	73	433	547	114
7 Rt	56	81	25	420	482	62
8 Rt	70	78	8	442	448	6
9 Lt	291	247	-44	361	395	34
10 Lt	380	475	95	546	519	-27

Table 24: Full Study Grasp and Release Test (GRT) Data

Without Glove				*With Glove*			
Hand	Pre	Post	Diff.	Hand	Pre	Post	Diff.
1 Rt	145	164	19	6 Rt	238	264	26
2 Rt	164	165	1	7 Rt	154	176	22
3 Rt	158	175	17	8 Rt	164	204	40
4 Lt	211	220	9	9 Lt	97	129	32
5 Rt	200	229	29	10 Lt	182	207	25
Averages	175.6	190.6	15	Averages	167	196	29

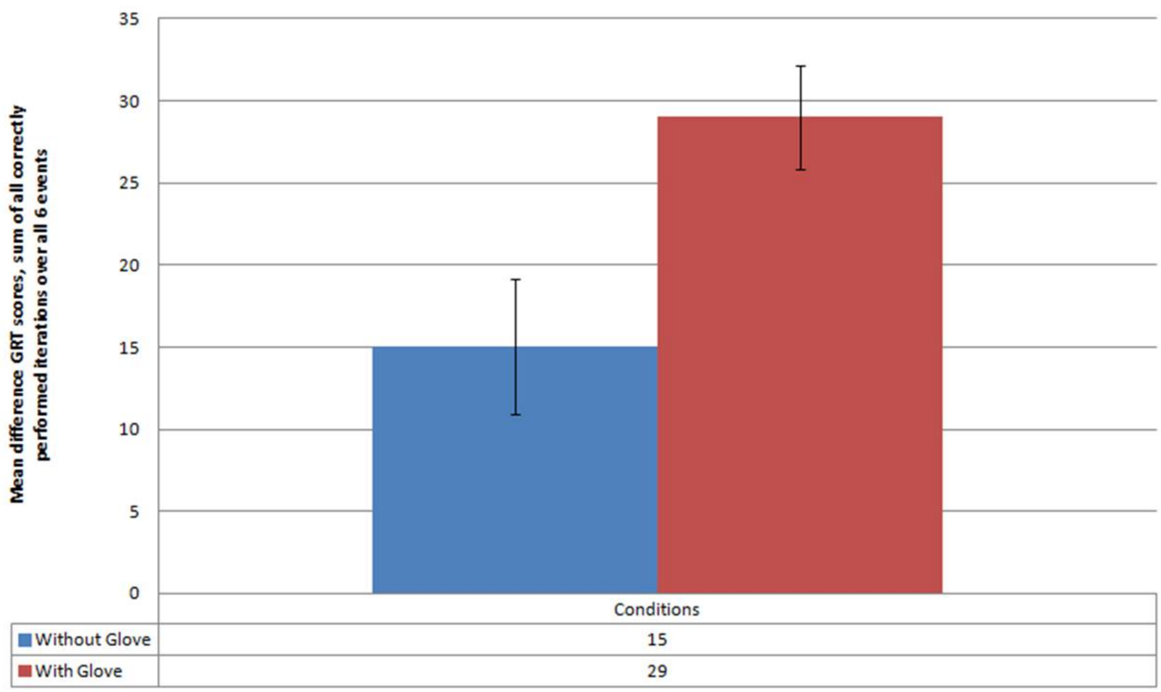


Figure 47: Graphical depiction of GRT results by condition.

maximum scores possible on the ARAT. We anticipated this possibility, as in order to qualify for our study, participants had to be able to activate the keys of the piano with each finger. Our inclusion criteria requires a level of hand use that causes them to come close to, or achieve, the maximum score on the ARAT. Thus, our results may be suffering from a ceiling effect. ARAT data are depicted in Tables 25 and 26.

6.3.2.6 *Passive Haptic Learning*

We did examine PHL in this study as well. However, the three evaluations of the weekly song all occurred after at least one active practice session. Thus, we did not establish the initial baseline, which would have shown a larger effect. The average reduction in song errors (screening for possible PHL effect) for the *without glove* group ($PHLmean_{without}$ = -12.78) was not significantly different from that of the *with glove* group ($PHLmean_{with}$ = -12.2).

Table 25: Full Study ARAT Data *Without Glove*

	Pre					Post					Diff.				
Hand	Grasp	Grip	Pinch	Gross	Total	Grasp	Grip	Pinch	Gross	Total	Grasp	Grip	Pinch	Gross	Total
1 Rt	18	11	14	9	52	18	11	17	9	55	0	0	3	0	3
2 Rt	18	11	18	9	56	18	10	18	9	55	0	-1	0	0	-1
3 Rt	16	11	13	9	49	16	12	14	9	51	0	1	1	0	2
4 Lt	18	12	17	9	56	18	12	17	9	56	0	0	0	0	0
5 Rt	18	12	13	9	52	18	12	16	9	55	0	0	3	0	3

Table 26: Full Study ARAT Data *With Glove*

	Pre					Post					Diff.				
Hand	Grasp	Grip	Pinch	Gross	Total	Grasp	Grip	Pinch	Gross	Total	Grasp	Grip	Pinch	Gross	Total
6 Rt	18	12	17	9	56	18	12	18	9	57	0	0	1	0	1
7 Rt	18	10	17	9	54	18	11	18	9	56	0	1	1	0	2
8 Rt	18	11	6	9	44	18	10	10	9	47	0	-1	4	0	3
9 Lt	17	11	15	5	48	17	12	13	8	50	0	1	-2	3	2
10 Lt	18	12	15	9	54	18	12	16	9	55	0	0	1	0	1

6.3.2.7 Qualitative Results

In this section, we consider the qualitative data collected using our Post Questionnaires. We analyzed data collected using the CUE Instrument in Appendix K. Graphic depictions of the post questionnaire results for *without glove* are displayed in Figures 48 through 50. Results of *with glove* data are shown in Figures 51 through 55. We found that both groups enjoyed playing the piano and perceived hand improvement in terms of sensation and motor abilities. Both groups also reported a general improvement in mood over the course of the study. Participants who wore the glove reported a higher degree of satisfaction with piano playing improvement than those participants who did not. The *without glove* group also did see a slightly higher difficulty in mastering a given song in one week, as seen in Figure 50. The *with glove* group had a higher percentage feel they had learned a new skill, not just performing rehab, than the *without glove* group (see Figures 50 and 53). Those who wore the glove felt that it aided in learning the songs, as shown in Figure 53. An additional set of questions were included in the *with glove* group questionnaire. The glove did not interfere with participants' daily activities, was comfortable, and did not cause embarrassment (see Figure 54). Interestingly, the *with glove* group also reported that the vibration did not interfere with daily activities, and that they found they tapped along with the song or could "hear" the song as it played in vibration form on their hand (see Figure 55).

The post-study questionnaires also asked participants for open comments about their experiences with the study. Half of the *without glove* group noted sensory improvements. One participant stated he "can feel heat of cup of coffee now, where prior to the study, the feeling of heat was 'delayed' when touching the hot object." Two others simply stated they noticed improvements in sensation, in general, in the hands. In terms of motor skills improvements, all but one participant stated they noticed improvements. Of these, one had began typing more and using "Dragon" dictation software less; another noted an improved ability to use scissors, open a bottle of pop, and to use a knife to cut meat. Another participant in this group said he saw improved movement and control, mostly when using a keyboard to type. These improvements in the *without glove* group may be attributed to the act of playing the piano, which required the use of all five fingers in a dexterous activity. Three of five participants in the *with glove* group stated they perceived improvements in their ability to feel with their hands. One participant in this group stated he had "better sensation in fingertips; can feel ridges (texture) in objects now which helps with picking up items." Another noted an increase of sensation in the fingertips, and an improvement in strength, especially in the left ring and right pinky fingers. She also stated that when she wore the glove on one hand that her other hand "wanted to 'do' something as well." Three of five in the *with glove* group also expressed an improvement in their ability to use their hands. One stated he could "open doors better, and it's easier to turn the key to start my car and that it's easier to use a letter opener now." Another participant in the *with glove* group found it "easier to hold a dish to wash."

The CUE data can be analyzed by summing up the participants' Likert scale responses to questions about their perceived ability to perform various tasks with their hands and arms. Summed scores may range from a minimum score of 31, which would result from selecting a one for each question, to a score of 217, which would be achieved by assessing a seven to each question. We observed a difference in the total scores of the *without glove* ($CUEmeandiff_{without}$ = -3.0) and *with glove* ($CUEmeandiff_{with}$ = 2.2) groups. However, the difference was not statistically significant (p = 0.09).

6.4 Discussion

In this study of people with tetraplegia, we found that there were improvements observed in somatosensation on the Semmes-Weinstein and 2-point discrimination tests

Table 27: Full Study CUE Data *Without Glove*

	Pre				Post				Diff.				
Hand	Tot.	Both	Rt.	Lt.	Tot.	Both	Rt.	Lt.	Tot.	Both	Rt.	Lt.	Int.
1 Rt	188	14	90	84	175	14	81	80	-13	0	-9	-4	-9
2 Rt	129	2	88	39	130	3	86	41	1	1	-2	2	-2
3 Rt	96	2	77	17	95	2	78	15	-1	0	1	-2	1
4 Lt	180	14	79	87	172	14	75	83	-8	0	-4	-4	-4
5 Rt	218	14	102	102	217	14	101	102	-1	0	-1	0	-1

Table 28: Full Study CUE Data *With Glove*

	Pre				Post				Diff.				
Hand	Tot.	Both	Rt.	Lt.	Tot.	Both	Rt.	Lt.	Tot.	Both	Rt.	Lt.	Int.
6 Rt	145	10	100	35	139	6	103	30	-6	-4	3	-5	3
7 Rt	201	14	99	88	212	14	103	95	11	0	4	7	4
8 Rt	177	14	80	83	180	14	79	87	3	0	-1	4	-1
9 Lt	124	3	77	44	142	6	82	54	18	3	5	10	10
10 Lt	164	12	74	78	156	11	72	73	-8	-1	-2	-5	-5

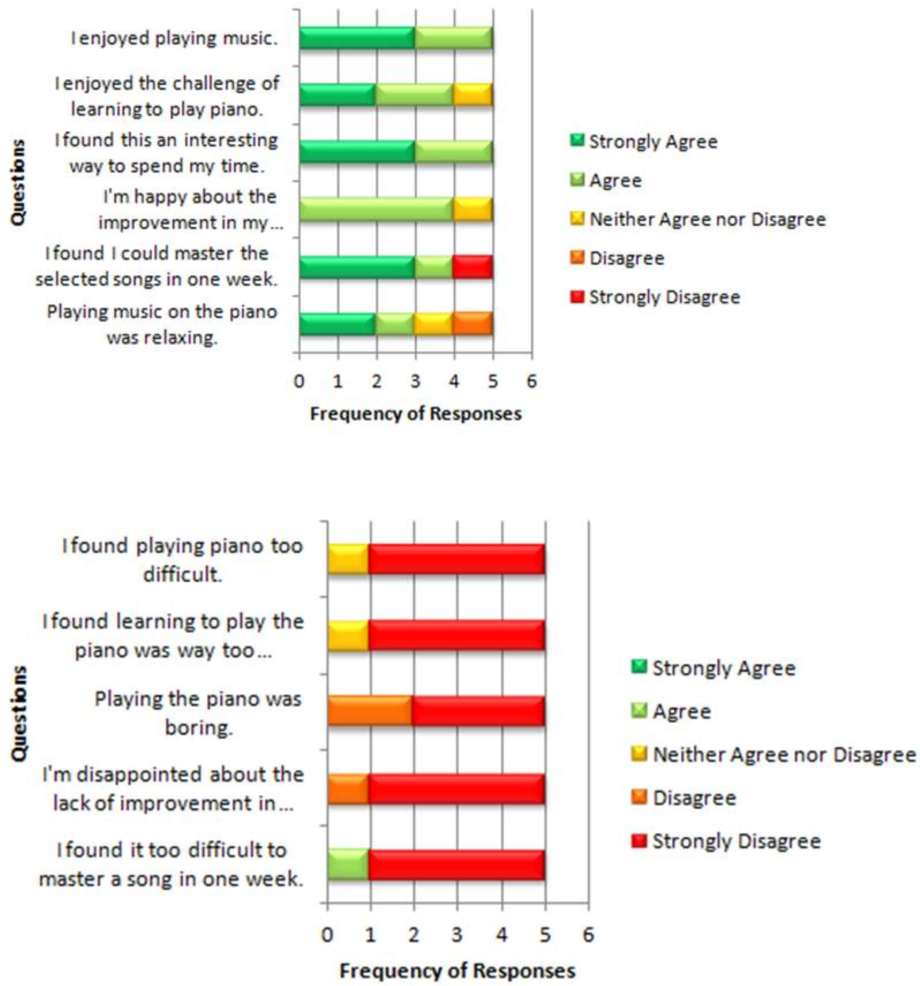


Figure 48: *Without Glove* Post Questionnaire Piano Playing Responses.

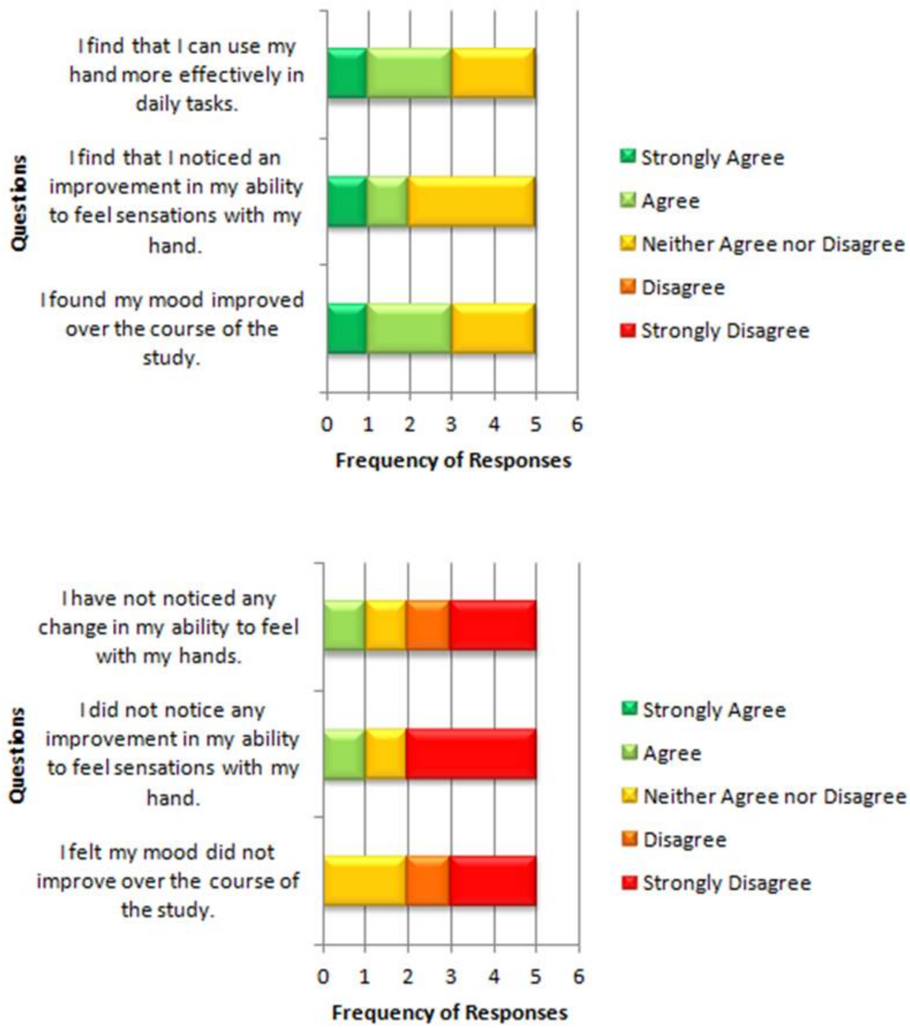


Figure 49: *Without Glove* Post Questionnaire Hand Change Responses.

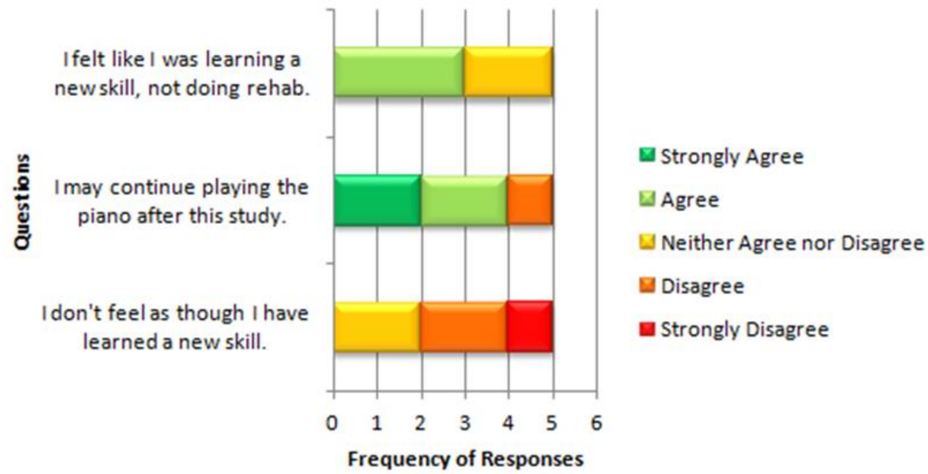


Figure 50: *Without Glove* Post Questionnaire Learning Responses.

of *with glove* participants. The MMT system may have provided them greater sensation without a corresponding change in strength, as indicated in the AMES results. Our results help support the suggestion by Sarabon and Dimitrijevic that perhaps the observations their team made of improvements in stroke patients using electrical stimulation may be accomplished through a mechanical stimulation method [81]. To explore the concept of PHR, we used vibration as a our mechanical stimulation. We also observed a significant increase in the number of correctly performed repetitions on the GRT, suggesting improved use of the hand for opening and closing, making it easier to handle objects. The changes in somatosensation and not strength suggest that the sensory changes are influencing hand and wrist control. Our finding of improved sensation possibly resulting in improved motor abilities supports the idea propsed by Hoffman et al. that "somatosensory stimulation can increase the cortical excitability of the motor cortex and corticospinal tract" [49]. Current research suggests that the brain is wired such that if one area is activated, it may cause firing in adjacent structures. The MMT system, which provided afferent stimulation resulting in stimulation of the sensory cortex, may be causing an increase in the excitability of the motor cortex. This hypothesis is supported by our observed improvements by

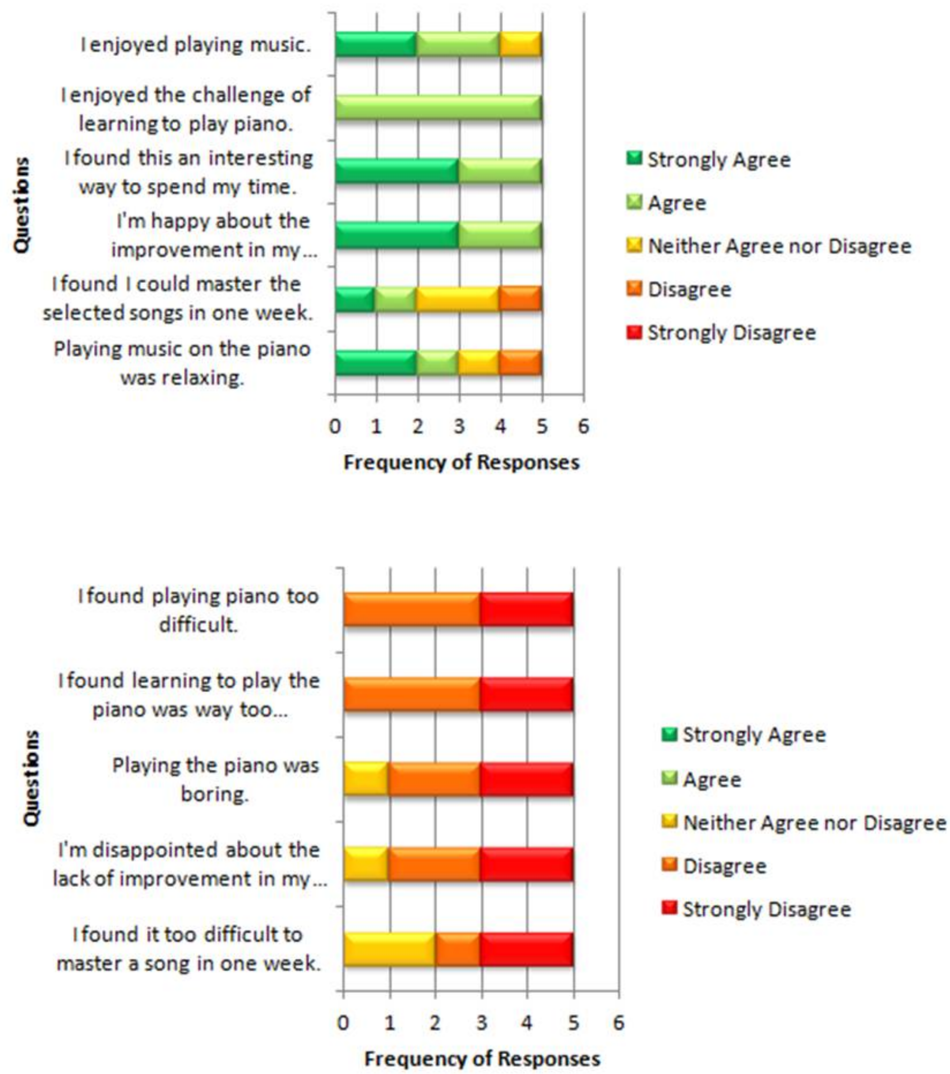


Figure 51: *With Glove* Post Questionnaire Piano Playing Responses.

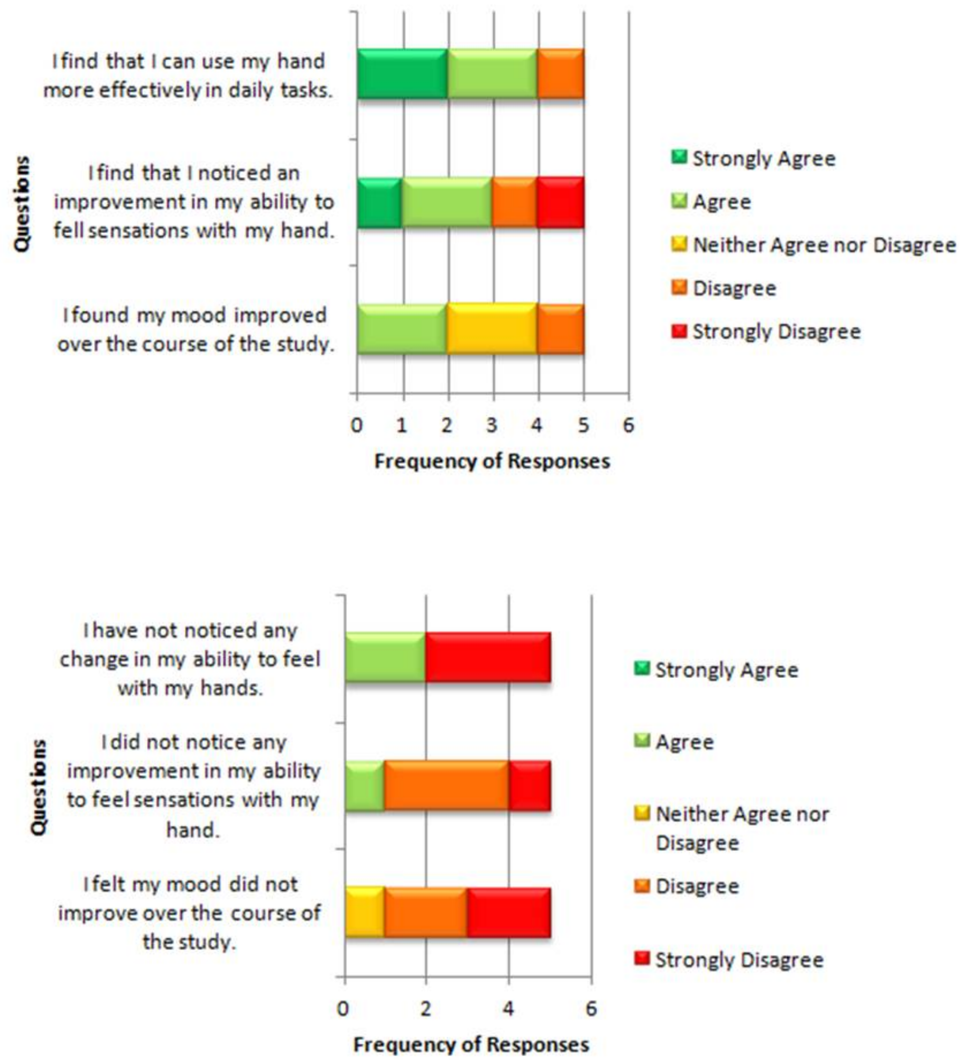


Figure 52: *With Glove* Post Questionnaire Hand Change Responses.

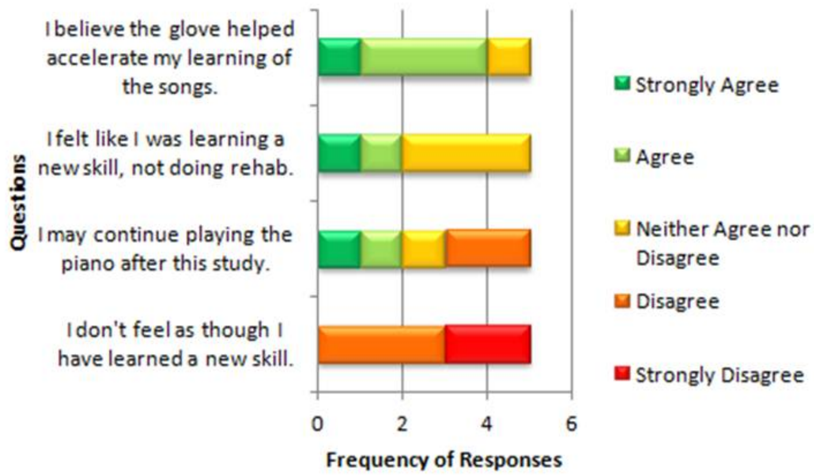


Figure 53: *With Glove* Post Questionnaire Learning Responses.

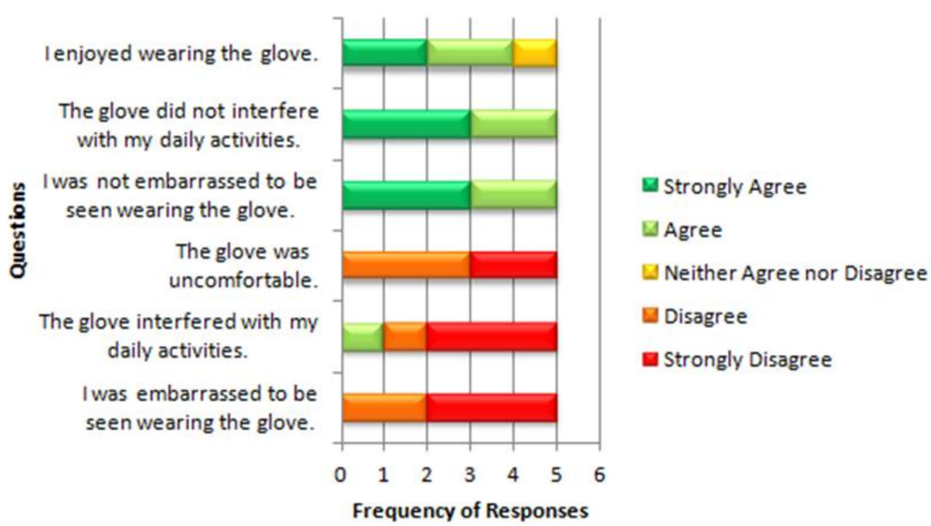


Figure 54: *With Glove* Post Questionnaire Wearability Responses.

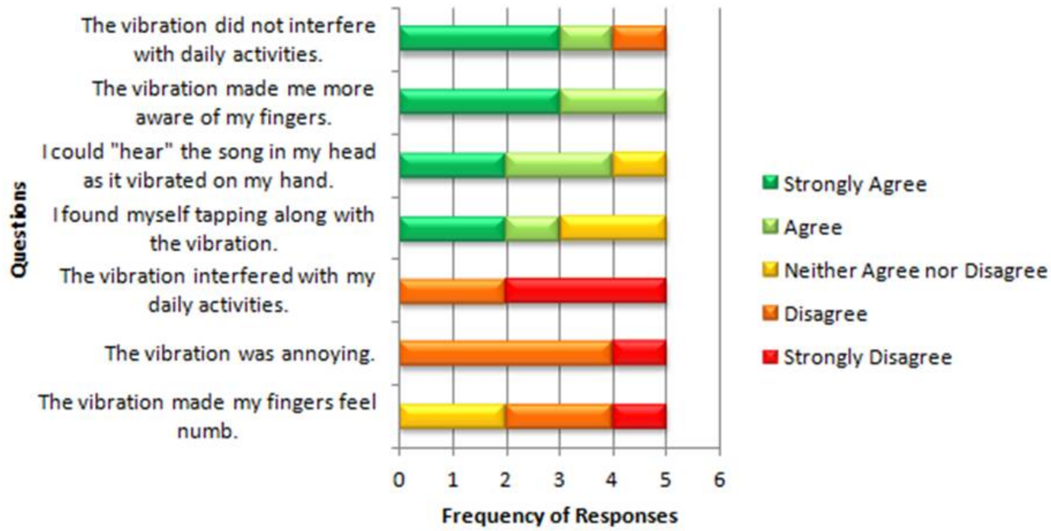


Figure 55: *With Glove* Post Questionnaire Vibration Responses.

participants on the GRT score.

We did not observe significant changes in learning during the full PHR study. One possible cause of these results is that we did not exclude any participants for the rehabilitation study who had formal piano playing background. Three "hands" (two in *without glove* condition, one in the *with glove* condition) had played piano before they were injured. We chose not to exclude these participants because the population of qualified persons was so small for this study. Another consideration is that while we employed real songs, they were generally older "camp" or "folk" songs that many of the participants did not recognize. Selecting a more popular song may encourage participation and should be a consideration in future song selection. Passive rehabilitation using the MMT system does demonstrate significant enough improvements in this preliminary study, particularly in sensation, to warrant further exploration with a larger population of participants.

Qualitative data from the questionnaires show that participants in the *with glove* group did seem to perceive greater improvements in sensation and motor abilities with the hand than the *without glove* group. Both groups did show improvements overall, however. The similar results may be due to the fact that the *without glove* group did still perform an activity that required fine use of the hands for piano playing, an activity which may have caused some rehabilitative effect. The additional improvements in sensation generally noted by the *with glove* group may attest to an additional effect caused by the vibro-tactile stimulation of the hands.

CHAPTER VII

DISCUSSION AND FUTURE WORK

In this chapter, we explore areas that might be expanded upon in the future in the fields of Passive Haptic Learning, Passive Haptic Rehabilitation, and user studies of these topics.

7.1 Within Subject Discussion

The PHR study revealed that the condition of active rehabilitation (piano playing) coupled with vibration stimuli from the MMT system provides improvements over the active rehabilitation activity alone. We also noted that those participants who first performed the *without glove* condition followed by the *with glove* condition saw improvements in sensation over and above those they achieved *without glove*. The Semmes-Weinstein data for both groups is shown in Figure 56.

The arrows indicate the change and direction, with an "up" arrow representing a decrease in diameter and therefore an improvement in sensation. The arrows without borders are participant hands that only performed the *with glove* condition. The arrows with dashed borders are participant hands that first underwent the *without glove* condition, followed by *with glove*, where the *with glove* condition is shown. The within subject data of those who first performed *without glove* followed by *with glove* is intriguing. Consider the Semmes-Weinstein data for the within subject group in Figure 57, depicting change from pre to post by site on a hand graphic for *without glove*, with Figure 58 when the subjects switched to using the glove.

While there seems to be a positive change in the improvement scores, it is not as large as the between-subjects experiment might suggest. Perhaps there is an order effect, where active practice alone already caused a certain amount of improvement.

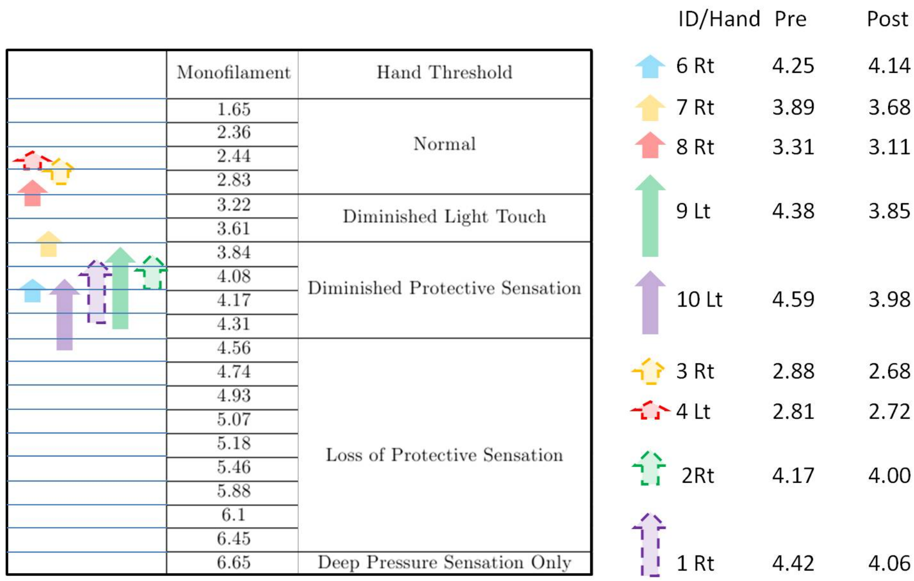


Figure 56: Graphical depiction of Semmes-Weinstein results. Arrows without line borders indicate participant hands that only performed the *with glove* condition. Arrows with dashed lines depict participant hands that first performed the *without glove* condition followed by the *with glove* condition.

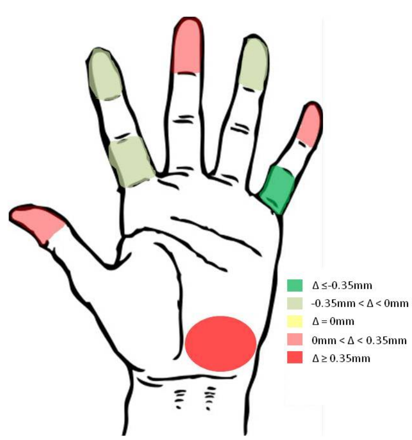


Figure 57: Change on Semmes-Weinstein pre to post within subject *without glove* condition.

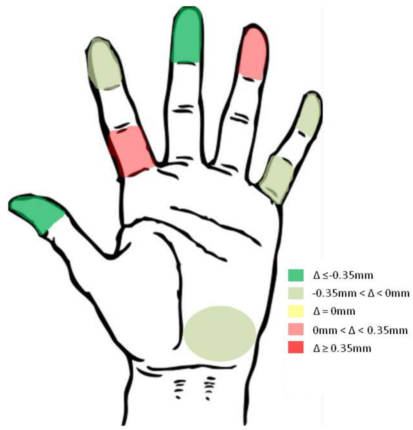


Figure 58: Change on Semmes-Weinstein pre to post within subject *with glove* condition.

While these within subject data are suggestive, a future study of a larger population who perform both conditions in a balanced randomized trial may help solidify these results.

Post-hoc analysis of Semmes-Weinstein pre values versus the change in Semmes-Weinstein post-intervention shows an interesting trend. We noted that those who started the study with sensation values closer to "normal" tended to see the smallest improvement, while much larger changes were observed in those starting out with sensation values furthest from "normal." See Figure 59. One possible explanation for this observation is that those who start with fairly good sensation do not have as much potential room to improve. A large study may allow us to determine the element of our population that may best be served by this intervention based off initial Semmes-Weinstein scores.

Another possible consideration is how long the benefits of these interventions last. Rehabilitative benefits may not persist long after a rehabilitation program is discontinued. Gladman revealed in his work "Improving Long-term Rehabilitation" that the benefits of rehabilitation do not persist and that there must be continual intervention in a life-long plan. He discusses the finding that "late" interventions in

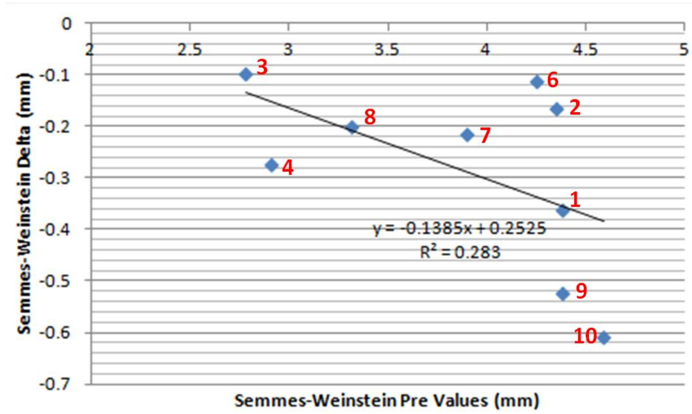


Figure 59: Comparison of pre-intervention Semmes-Weinstein values with change in Semmes-Weinstein. "Hand" ID numbers are indicated in red.

persons with stroke, long after they leave inpatient care (months to years) may still provide benefits to the patient. Rehabilitative activities and interaction with medical professionals also appears to improve the psychological state of a stroke patient after he leaves inpatient care. We see a similar argument for long-term rehabilitation activities in a paper by DeVivo, "Recent Trends in Spinal Cord Injury Rehabilitation Practices & Outcomes." DeVivo reveals that persons with SCI who were involved in greater than 40 hours of outpatient rehabilitation had a 10.4 increase in their Functional Independence Measure (FIM) versus 6.3 for persons who underwent 0 hours of outpatient rehabilitation [31]. These FIM scores were taken at the time of discharge and again a year later. These discussions support the idea that rehabilitation may provide more benefits in the long run when some degree of rehabilitative activity is performed throughout life. The benefits to the patient appear to be not only physical, but also psychological. A longitudinal study where evaluations are done months after the intervention may reveal if the changes are more than temporary. It may be that a participant must continue to use the MMT system to maintain the benefits. Should long-term use be required, ensuring the rehabilitative exercise is delivered in an engaging and interesting form becomes even more important to keep patients performing these beneficial activities.

We were pleased with the use compliance of the participants in the study. We collected on/off and accelerometer data, which is located in Appendix U. ID numbers 1-4 are "hands" that were within subject, participating *without glove* followed by *with glove*. ID numbers 6-10 were "hands" that only participated in the *with glove* group. ID 5 did not use the glove after performing the *without glove* condition. Average minutes of usage is calculated assuming five days a week over an eight week period of use. The usage data range from a total of 259 minutes to 7983 minutes. The average number of minutes over the entire study of the nine "hands" was 3396 with an average usage per week of 85 minutes. The "hands" that had the two outlier low values (ID 1 and 10) had data collection errors due to hardware issues that arose during the study. The "hands" of ID 1 and 10 belong to the same participant, run at different points. This participant also had some home and work conflicts which made it difficult to achieve the desired usage goals. When this participant's usage values are removed, the daily average use value is 104.7 minutes, which is closer to our goal of 120 minutes per day.

We then compared usage data to improvements on the Semmes-Weinstein test. We found that, contrary to our hypothesis, greater usage did not correlate to greater improvements (which would be indicated by more "negative" values in the change of the Semmes-Weinstein, as this indicates a reduction in the diameter of monofilament the participant could feel). See Figure 60 (since the usage data for hands #1 and #10 are unreliable, we do not include them in the graph or regression line calculation). Future studies should consider this comparison to see if a larger number of participants influences this trend.

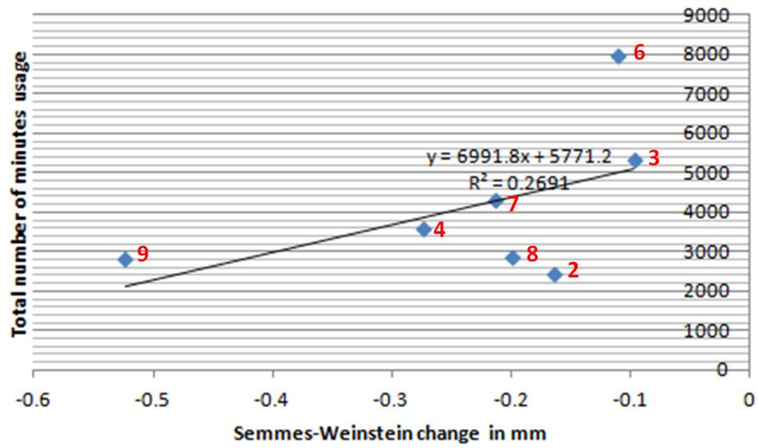


Figure 60: Change in Semmes-Weinstein monofilament diameter compared to usage data in minutes. "Hand" ID numbers are indicated in red.

7.2 Vibration Motor Placement

We asked users of the Passive Haptic Rehabilitation study to wear the MMT glove for at least two hours a day, five days a week. This necessitated the placing of the vibration motors on the backs of the fingers, to minimize their interference with daily activities of living. A future study would assess benefits of placing the vibration sources in various locations on the fingers. We would ideally explore the differences between dorsal, radial, and palmer placement. Previous work by Lee [63] and Tan [90] suggest that placement of vibration stimuli on the hands and the wrist in wearable haptic devices does have an impact on what the wearer can perceive in terms of messages encoded in the form of vibration stimulus, as discussed earlier in this dissertation. We should also consider using different form factors for the delivery of vibration stimulus. Smaller motors may interfere less with daily activities and improve comfort.

7.3 fMRI Studies

We believe that the vibration may be causing stimulation of the sensory cortex, resulting in a corresponding firing in the motor cortex [49]. Such stimulation may result in measurable changes in blood flow to the brain in those regions on the sensory and motor cortex that are tied to the areas undergoing stimulation. This effect was noted in a study we discussed previously by Golaszewski et al. [43]. Golaszewski et al. observed that participants who wore a whole-hand electrical stimulation glove showed an increase in the number of voxels (volume of pixels as revealed in fMRI results) activated when they performed the finger-tapping task after wearing the glove for 20 minutes, when compared to the same measurements performed prior to wearing the glove. We propose fMRI studies using the MMT system in order to determine if a similar outcome is possible using vibration as opposed to electrical stimulation. A possible study design would have a group of participants (injured or able-bodied) undergo fMRI scans prior to using the system. While in the fMRI, the participants would perform a specific finger tapping sequence, mapping the blood flow in the regions that are responsible for finger control. After using the MMT system for 8 weeks, we would again use the fMRI to visualize the blood flow in the brain while performing a finger tapping task. We could then measure the differences, if any, between the scans to determine if changes in areas of activity have taken place as a result of the application of vibration.

7.4 Automation of Process

When engaging participants in the active rehabilitation portion, specifically playing songs on the piano, a researcher was with the participant, directing the overall conduct of the activity. However, we would ideally have an automated program that would allow a participant to conduct the sessions without a researcher or therapist. In order to accomplish this, the system would need to "read" the participant's re-starts when practicing, know when to replay the passages for the user, and note subtleties such as noticing when the participant is using the wrong fingering for the song or is getting tired toward the end of a session. The complex interplay of researcher or therapist and participant needs further study and examination.

7.5 Other Instruments / Games

An important aspect of rehabilitation is motivation [16, 26, 66]. If a participant does not enjoy or is not challenged by an activity, he or she is less likely to continue to perform the rehab on his or her own. One way to approach this problem is to incorporate vibrotactile stimulation in several forms. We could use the MMT system to train participants on other musical instruments (guitar, drums, woodwinds, strings) or video games. As the majority of initial spinal cord injuries occur in males, ages 16-30 [7], we believe that video games might better appeal to this population [26, 45]. Oftentimes, these patients are put into the same room with another injured person. Competitive gaming might encourage roommates to engage in even more rehab in trying to beat another player's score. Competition might also be accomplished remotely, using Internet-based games. Incorporating vibration into existing games may also permit injured persons to compete with their uninjured friends in games that they already enjoy online.

7.6 Study Size

In the case of the rehabilitation study, the inclusion requirements were such that our potential population of participants was quite small. For future study, we would expand the study sites to include spinal cord rehabilitation centers all over the country. We would also increase the number of researchers authorized and able to execute the study in order to accomplish more over a smaller time frame. Our study did show great potential for the MMT system, however it amounts to a pilot study. A full study would allow us to validate the findings and refine our procedures.

7.7 Song Selection and Complexity

The songs used for this study were all simple and limited to just the melody. Future study could include harmony, chords and other more complicated aspects of music.

We would also seek out more recognizable tunes, such as modern music that participants may know. There was a great increase in the likability of songs that our participants recognized (such as “Ode to Joy”). We also need to closely consider complexity. Songs that were 6-8 phrases with heavy repetition were favored far more than those that were of 8-10 phrases and/or have little or no repetition.

CHAPTER VIII

CONCLUSION

We have demonstrated the feasibility of the concepts of Passive Haptic Learning and Passive Haptic Rehabilitation using the Mobile Music Touch system, a passive haptic device. In order to explore the rehabilitative effects of vibration applied to the hands, we improved the MMT device iteratively for spinal cord injury persons to wear and use easily. We also articulated a set of design features that accommodates this population of users.

Using the Mobile Music Touch system, we demonstrated that Passive Haptic Learning with the audio+vibration condition and the vibration only condition resulted in significantly fewer errors while playing simple piano passages after performing a distractor task than audio alone or the control conditions. However, we noted that participants reported a higher degree of frustration when performing the distractor task while experiencing the audio+vibration condition than vibration alone. This finding supported our decision to perform the Passive Haptic Rehabilitation study using the vibration alone condition, making it more acceptable for daily, extended wear.

Participants with spinal cord injury who used the Mobile Music Touch system in active and passive rehabilitation demonstrated a greater degree of improvement in sensitivity and fine motor control of the hands than those who only performed active rehabilitation, specifically playing songs on a piano keyboard. Further study is warranted, and we have outlined a set of experiments to continue to explore the possibilities of Passive Haptic Rehabilitation.

APPENDIX A

FIRST GLOVE STUDY QUESTIONNAIRE

MMT Glove Wearability Survey 2009

Introduction:

Thank you for your participation in the Mobile Music Touch (MMT) project. Please complete this brief questionnaire about your experiences while wearing the various gloves. Your participation will help us select the best glove design for future MMT testing and use.

There are no right or wrong answers. We are interested in your opinions and experiences. Your responses will be kept confidential.

INSTRUCTIONS:

Please read each question carefully and give the response that best fits with your experience. If you do not understand a question, please do not hesitate to ask for help.

How satisfied are you with

	Very Dissatisfied	Somewhat Dissatisfied	Somewhat Satisfied	Very Satisfied
The overall comfort wearing the glove				
Fit of the glove				
The durability of the glove (fabric and fasteners – such as Velcro or snaps)				

Are there any aspects of the glove that you would like to see improved (material selection, fasteners, hardware, wiring, fit)?

____

____

____

____

____

____

How was the fit and function?

	Strongly Disagree	Disagree	Agree	Strongly Agree
The glove was easy to put on				
The glove was easy to remove				
The weight of the glove including all the associated hardware was not irritating				
The weight of the glove including all the associated hardware was not noticeable				
The hardware did not rub or irritate the hand or arm				
The hardware did not interfere with daily				

activities				
You could easily determine which motor was vibrating				
The glove work reliably over the course of a session				

How long did you wear the glove per day?

__Less than 2 hours

__ 2 – 3 hours

__ 3 – 4 hours

__4 – 5 hours

__5 – 6 hours

__6 + hours

How long do you think did you experience vibration in the fingers of the glove in a single session??

__Less than 2 hours

__ 2 – 3 hours

__ 3 – 4 hours

__4 – 5 hours

__5 – 6 hours

__6 + hours

What do you think the ideal session length should be?

__Less than 2 hours

__ 2 – 3 hours

__ 3 – 4 hours

__4 – 5 hours

__5 – 6 hours

__6 + hours

What do you think the length of the longest tolerable session length should be?

__Less than 2 hours

__ 2 – 3 hours

__ 3 – 4 hours

__4 – 5 hours

__5 – 6 hours

__6 + hours

Are there any activities that the glove interfered with? (Y/N) _______________

If Yes, please list: ____

____

If Yes, please indicate how it interfered:

____

____

Comment about your overall experience wearing the glove

Please tell us any issues concerning the glove (fit, wearibility, comfort, interference or assistance with day-to-day activities):

____

Please use the space below for any additional comments, suggestions or questions you have about your experience with the MMT glove.

Thank you for your participation

APPENDIX B

SECOND GLOVE STUDY QUESTIONNAIRE

MMT Glove Wearability Survey 2010

Introduction:

Thank you for your participation in the Mobile Music Touch (MMT) project. Please complete this brief questionnaire about your experiences while wearing the various gloves. Your participation will help us select the best glove design for future MMT testing and use.

There are no right or wrong answers. We are interested in your opinions and experiences. Your responses will be kept confidential.

INSTRUCTIONS:

Please read each question carefully and give the response that best fits with your experience. If you do not understand a question, please do not hesitate to ask for help.

How satisfied are you with:

	Very Dissatisfied	Somewhat Dissatisfied	Somewhat Satisfied	Very Satisfied
The overall comfort wearing the glove				
Fit of the glove				
The durability of the glove (fabric and fasteners – such as Velcro or snaps)				

Are there any aspects of the glove that you would like to see improved (material selection, fasteners, hardware, wiring, fit)?

____

____

____

How was the fit and function?

	Strongly Disagree	Disagree	Agree	Strongly Agree
The glove was easy to put on				
The glove was easy to remove				
The weight of the glove including all the associated hardware was not irritating				
The weight of the glove including all the associated hardware was not noticeable				
The hardware did not rub or irritate the hand or arm				
The hardware did not interfere with daily activities				
You could easily determine which motor was vibrating				
The glove work reliably over the course of a session				

How long did you wear the glove per day?

__Less than 2 hours

__ 2 – 3 hours

__ 3 – 4 hours

__4 – 5 hours

__5 – 6 hours

__6 + hours

How long do you think did you experience vibration in the fingers of the glove in a single session??

__Less than 2 hours

__ 2 – 3 hours

__ 3 – 4 hours

__4 – 5 hours

__5 – 6 hours

__6 + hours

What do you think the ideal session length should be?

__Less than 2 hours

__ 2 – 3 hours

__ 3 – 4 hours

__4 – 5 hours

__5 – 6 hours

__6 + hours

What do you think the length of the longest tolerable session length should be?

__Less than 2 hours

__ 2 – 3 hours

__ 3 – 4 hours

__4 – 5 hours

APPENDIX C

PHL PRE QUESTIONNAIRE

Participant ID: ________________

Date: ________________________

MMT Passive Haptic Learning Study
2010 Pre-Questionnaire

Introduction:

Thank you for your participation in the Mobile Music Touch (MMT) project. Please complete this brief questionnaire before you participate so we can collect needed participant data.

Your responses will be kept confidential.

INSTRUCTIONS:

Please read each question carefully and give the response that best fits your background and experience.

1. Have you ever played a musical instrument? (yes / no)
2. If yes, which instrument? ______________________________
3. Do you have any formal musical education (instrument or voice lessons)? If yes, how many years per instrument / voice? ______________________________

   ____
4. Do you know how to read music? (yes / no)
5. Have you ever listened to a piece of music then played it without any instruction on how to do it? If so, what instrument? ______________________________

Thank you for your participation

APPENDIX D

PHL POST QUESTIONNAIRE

Participant ID: ____________________

Date: ________________________

MMT Passive Haptic Learning Study
2010 Post-Questionnaire

Introduction:

Thank you for your participation in the Mobile Music Touch (MMT) project. Please complete this post-questionnaire that helps us assess your experience using the MMT system.

There are no right or wrong answers. Your responses will be kept confidential.

INSTRUCTIONS:

Please read each question carefully and give the response that best fits your experience.

Answer each of the questions below on a scale of 1 to 5, where 1 is strong disagree and 5 is strongly agree. If the question asks about vibration or music when you did not receive these, then simply write "N/A" for the question.

1. "I believe the GRE test was more difficult to complete with audio."

(Strongly Disagree) (Neutral) (Strongly Agree)

1 2 3 4 5

2. "When doing the vibration only task, I could still hear the music in my head."

(Strongly Disagree) (Neutral) (Strongly Agree)

1 2 3 4 5

3. "I felt the vibration was too weak to feel."

(Strongly Disagree) (Neutral) (Strongly Agree)

1 2 3 4 5

4. "The vibration was annoying at times."

(Strongly Disagree) (Neutral) (Strongly Agree)

1 2 3 4 5

5. "The glove was comfortable to wear."

(Strongly Disagree) (Neutral) (Strongly Agree)

1 2 3 4 5

6. "I was able to focus on the GRE test."

(Strongly Disagree) (Neutral) (Strongly Agree)

1 2 3 4 5

Thank you for your participation

APPENDIX E

NASA TLX QUESTIONNAIRES

NASA Task Load Index

Hart and Staveland's NASA Task Load Index (TLX) method assesses work load on five 7-point scales. Increments of high, medium and low estimates for each point result in 21 gradations on the scales.

Name	Task	Date

Mental Demand — How mentally demanding was the task?

Very Low — Very High

Physical Demand — How physically demanding was the task?

Very Low — Very High

Temporal Demand — How hurried or rushed was the pace of the task?

Very Low — Very High

Performance — How successful were you in accomplishing what you were asked to do?

Perfect — Failure

Effort — How hard did you have to work to accomplish your level of performance?

Very Low — Very High

Frustration — How insecure, discouraged, irritated, stressed, and annoyed wereyou?

Very Low — Very High

Task Demand Comparisons

For each of the following, please place a mark to indicate which of the two was more demanding for you.

1.	__________ Physical Demand	OR	__________Mental Demand
2.	__________ Temporal Demand	OR	__________Mental Demand
3.	__________ Performance	OR	__________Mental Demand
4.	__________ Frustration level	OR	__________Mental Demand
5.	__________ Effort	OR	__________Mental Demand
6.	__________ Temporal Demand	OR	__________Physical Demand
7.	__________ Performance	OR	__________Physical Demand
8.	__________ Frustration level	OR	__________Physical Demand
9.	__________ Effort	OR	__________Physical Demand
10.	__________ Temporal Demand	OR	__________Performance
11.	__________ Temporal Demand	OR	__________Frustration level
12.	__________ Temporal Demand	OR	__________Effort
13.	__________ Performance	OR	__________Frustration level
14.	__________ Performance	OR	__________Effort
15.	__________ Effort	OR	__________Frustration level

APPENDIX F

HANDEDNESS INVENTORY

AMES Study: Effects of Somatosensation on Motor Recovery
Subject Medication Information

Edinburgh Handedness Inventory[1]

Subject ID number:__________________ Date:________________
Investigator initials:__________________

Please indicate with a check (✓) your preference in using your left or right hand in the following tasks.

Where the preference is so strong you would never use the other hand, unless absolutely forced to, put two checks (✓✓).

If you are indifferent, put one check in each column (✓ | ✓).

Some of the activities require both hands. In these cases, the part of the task or object for which hand preference is wanted is indicated in parentheses.

Task / Object	Left Hand	Right Hand
1. Writing		
2. Drawing		
3. Throwing		
4. Scissors		
5. Toothbrush		
6. Knife (without fork)		
7. Spoon		
8. Broom (upper hand)		
9. Striking a Match (match)		
10. Opening a Box (lid)		
Total checks:	LH =	RH =
Cumulative Total	CT = LH + RH =	
Difference	D = RH – LH =	
Result	R = (D / CT) × 100 =	
Interpretation: (Left Handed: R < -40) (Ambidextrous: -40 ≤ R ≤ +40) (Right Handed: R > +40)		

[1] Oldfield, R. C. (1971). The assessment and analysis of handedness: The Edinburgh inventory. *Neuropsychololgia*, *9*, 97-113.

APPENDIX G

PHR MUSICAL ABILITY PRE QUESTIONNAIRE

Participant ID: ________________
Date: ______________________

MMT Passive Haptic Rehabilitation Study
2011 Pre-Questionnaire

Introduction:

Thank you for your participation in the Mobile Music Touch (MMT) project. Please complete this brief questionnaire before you participate so we can collect needed participant data.

Your responses will be kept confidential.

INSTRUCTIONS:

Please read each question carefully and give the response that best fits your background and experience.

1. Have you ever played a musical instrument? (yes / no)
2. If yes, which instrument? ______________________________
3. Do you have any formal musical education (instrument or voice lessons)? If yes, how many years per instrument / voice? ______________________________

   ____
4. Do you know how to read music? (yes / no)
5. Have you ever listened to a piece of music then played it without any instruction on how to do it? If so, what instrument? ______________________________

Thank you for your participation

APPENDIX H

GRASP AND RELEASE TEST EVALUATION FORM

Grasp and Release Test (GRT)

Subject ID: ___ ___ ___ ___ **Protocol Number: 474**

Evaluator: ______________________________ **Date: _______________**

Session Information:
Pre-Treatment: __________ Mid-Treatment: __________ Post-Treatment: __________

Position at Table:
Knee-to-table: ______________ Seat Angle: ______________
Wheelchair-to-table: ______________
Midline to Barrier: ______________

Wheelchair description:
Wheelchair ref point:

Splint Usage/Positioning:
Do you have a splint? Y☐ N☐
If Yes, do you use it? Y☐ N☐ How Frequently? ________________________________

NOTE: If subject has a splint, please test with and without the splint

Functional Splint (+): Type of Splint: ____
Wrist Position (+): ________ (deg) Direction F ______ E ______

Functional Splint (-): Type of Splint: ____
Wrist Position (-): ________ (deg) Direction F ______ E ______

Exercise Splint: ____

Checklist:
ROM completed? Y☐ N☐

1

Grasp and Release Test (GRT)

Subject ID: ___ ___ ___ ___ **Protocol Number: 474**

Evaluator: _____________________________ **Date: ______________**

Pre-Test Start Time: ____________

* 1 = prox muse 3 = force
2 = position 4 = control 5 = other

	Pass?	* Failure Code (list up to three)	
Peg	Y ☐ N ☐		
Weight	Y ☐ N ☐		
Fork	Y ☐ N ☐		
Block	Y ☐ N ☐		
Can	Y ☐ N ☐		
Tape	Y ☐ N ☐		

Comments:

____
____
____
____

2

Grasp and Release Test (GRT)

Subject ID: ___ ___ ___ ___ **Protocol Number: 474**

Evaluator: ______________________________ **Date: _______________**

Main Test Start Time: _____________
Comp = # Attempts = # Failures

* 1 = prox muse 3 = force
2 = position 4 = control 5 = other

	#Att	#Fail	#Comp (Att-Fail)	Comments	Failure Code
Fork					
Can					
Weight					
Tape					
Block					
Peg					

Comments:
____
____
____
____

Stop time: _____________ **Elapsed Time:** ☐ **Pre-Test** ☐ **Main Test**

Have you given this test your best effort?	Y ☐	N ☐
Was the test board at an optimal position?	Y ☐	N ☐
Was your performance impaired by the evaluator?	Y ☐	N ☐

	(+)		(-)	
Peg	Y ☐	N ☐	Y ☐	N ☐
Weight	Y ☐	N ☐	Y ☐	N ☐
Fork	Y ☐	N ☐	Y ☐	N ☐
Block	Y ☐	N ☐	Y ☐	N ☐
Can	Y ☐	N ☐	Y ☐	N ☐
Tape	Y ☐	N ☐	Y ☐	N ☐

Comments:
____
____
____
____

3

APPENDIX I

ACTION RESEARCH ARM TEST EVALUATION FORM

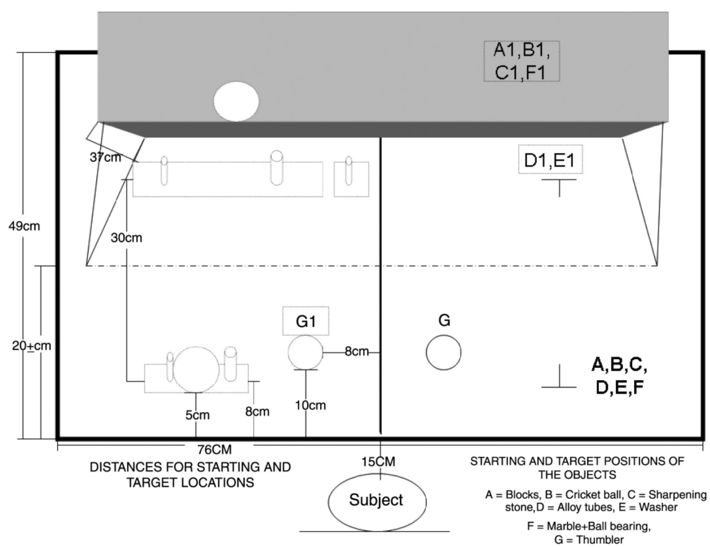
Subject ID: ___ ___ ___ ___ Protocol Number: _______________
Evaluator:___________________________ Date: __________________________

Action Research Arm Test

Prepare for test:
Evaluator kit: (assembled in plastic tool box)

- Chair without arm rests Table
- Mat
- Wooden blocks
- Cricket ball
- Sharpening Stone
- Alloy Tubes and 2 planks
- 1 Washer and bolt and 1 plank
- 2 tobacco tin lids
- A 37-cm-high shelf
- 2 glasses
- Marbles
- Ball bearings

Set up table: (from Yozbatiran N, Der-Yeghiaian and Cramer S. 2008. A standardized approach to performing the Action Research Arm Test, *Neuralrehabil Neural Repair*, 22; 78.)



Before start of test:
Range hand fully TEN TIMES from full finger and thumb flexion with wrist extended to full finger and thumb extension with wrist flexed. Hold each extreme position for count of 5. All of the fingers are ranged simultaneously.

Subject ID: ___ ___ ___ ___ Protocol Number: _______________

Evaluator:___________________________ Date: __________________________

Session Information: (date)

Pre-Treatment: ___________ Post Tx.: ___________ Follow up.: ___________

Overview: Subject must be seated upright, either in a standard chair without arm rests, or in their wheelchair with arm rests removed. You may use a pad to help position. REMIND THE SUBJECT FREQUENTLY THROUGHOUT THE TEST TO MAINTAIN AN UPRIGHT POSITION.

Position at Table:

Position subject 15 cm from the edge of the table (measured from mid-sternum to edge of table)

Remove leg rests to position feet flat on the floor – use a step or further support to keep hips at 90°

Wheelchair description: (type)

Cushion: (type)

Comments: ____

____

Scoring Overview:

1. Each task is read aloud to the subject.
2. May also provide visual demonstration.
3. The subject is allowed to practice the task repeatedly to ensure they understand.
4. Both upper extremities are tested separately.
5. The subject performs each task until the task is completed or a time limit of 60 seconds.

Scoring:

- "0" = unable to complete the task at all – any parts of the arm or hand movements with in the 60 secs. allotted
- "1" = can only complete the task partially within the 60 secs. Quality of movement and posture are not scored and do not matter; for grip, pinch, grasp – they MUST demonstrate the distal component and not just the reaching component
- "2" = task is completed either "with great difficulty" or "takes abnormally long".
  - "great difficulty" = 1) abnormal hand movement components (eg. Wrong grasp); 2) abnormal arm movement components (eg., elbow does not flex as required, 3) abnormal body posture.
  - Abnormal amount of time = > 5 secs.

Max SCORE = 57

Please also see the individual subscales for specific scoring instructions.

Subject ID: ___ ___ ___ ___ Protocol Number: _______________
Evaluator:___________________________ Date: __________________________

Test Number Item		Score
Grasp Subscale	**Left**	**Right**
Block, 10 cm3	**0 1 2 3**	**0 1 2 3**
Block, 2.5 cm3	**0 1 2 3**	**0 1 2 3**
Block, 5 cm3	**0 1 2 3**	**0 1 2 3**
Block, 7.5 cm3	**0 1 2 3**	**0 1 2 3**
Cricket Ball	**0 1 2 3**	**0 1 2 3**
Sharpening stone	**0 1 2 3**	**0 1 2 3**
Subtotal	**____/18**	**____/18**
Grip Subscale		
Pour water from one glass to another	**0 1 2 3**	**0 1 2 3**
Displace 2.25-cm alloy tube from one side of table to other	**0 1 2 3**	**0 1 2 3**
Displace 1-cm alloy tube from one side of table to the other	**0 1 2 3**	**0 1 2 3**
Put washer over bolt	**0 1 2 3**	**0 1 2 3**
Subtotal	**____/12**	**____/12**
Pinch Subscale		
Ball bearing, held between ring finger & thumb	**0 1 2 3**	**0 1 2 3**
Marble, held between index finger & thumb	**0 1 2 3**	**0 1 2 3**
Ball bearing, held between middle finger & thumb	**0 1 2 3**	**0 1 2 3**
Ball bearing, held between index finger & thumb	**0 1 2 3**	**0 1 2 3**
Marble, held between ring finger & thumb	**0 1 2 3**	**0 1 2 3**
Marble, held between middle finger & thumb	**0 1 2 3**	**0 1 2 3**
Subtotal	**____/18**	**____/18**
Gross Movement Scale		
Hand to behind the head	**0 1 2 3**	**0 1 2 3**
Hand to top of head	**0 1 2 3**	**0 1 2 3**
Hand to mouth	**0 1 2 3**	**0 1 2 3**
Subtotal	**____/9**	**____/9**
Total	**____/57**	**____/57**

Comments:

APPENDIX J

ASSISTED MOVEMENT ENHANCED SENSATION EVALUATION

AMES TEST

Participant	
Date	

Grasp Joint Position	Wrist Joint Position

Grasp Strength Test		Wrist Strength Test	
Extension	Flexion	Right	Left

APPENDIX K

CUE INSTRUMENT

CAPABILITIES OF UPPER EXTREMITY QUESTIONNAIRE

This questionnaire is designed to find out how well you are able to use your arms and hands. I will ask you about a number of actions which some people with spinal cord injury have limitations performing. Please consider whether, on an average day, you have difficulties or limitations performing these actions. By this I mean difficulty doing the action, or trouble doing it as often as you would like or need in order to complete everyday activities. Consider only the specific part of your arm or hand asked about in each question. For example, if asked about pulling something with your arm, do not worry about whether or not you can grab it with your hand.

Answer each question on a scale of 1 to 7, where 7 is the best – you have no difficulty or limitation doing the action, and 1 is the worst – you are totally limited and can't do it at all.

Totally Limited	Extremely Limited	Very Limited	Moderately Limited	Some Limitation	A little Limited	Not at all Limited
1	2	3	4	5	6	7

	Totally Limited	Extremely Limited	Very Limited	Moderately Limited	Some Limitation	A little Limited	Not at all Limited
THE FOLLOWING QUESTIONS ARE ABOUT YOUR ABILITY TO REACH OR LIFT							
1. Think about reaching out with your arm to touch something directly in front of you that is at shoulder level:							
...how limited are you doing this using your RIGHT ARM	1	2	3	4	5	6	7
...how limited are you doing this using your LEFT ARM?	**1**	**2**	**3**	**4**	**5**	**6**	**7**
2. Think about raising your arm directly over your head, with your arm straight:							
...how limited are you doing this motion using your RIGHT ARM?	1	2	3	4	5	6	7
...how limited are you doing this motion using your LEFT ARM?	**1**	**2**	**3**	**4**	**5**	**6**	**7**
3. Think about reaching down to touch the floor and sitting back up straight, without hooking with your other arm or using it to pull yourself up:							
...how limited are you doing this with your RIGHT HAND?	1	2	3	4	5	6	7
...how limited are you doing this with your LEFT HAND?	**1**	**2**	**3**	**4**	**5**	**6**	**7**

Name\ID: Date: Capabilities of Upper Extremity Instrument - CUE ™ V 1.1/ p2

	Totally Limited	Extremely Limited	Very Limited	Moderately Limited	Some Limitation	A little Limited	Not at all Limited
4. Think about raising a 5-pound object like a heavy blanket over your head using both arms. (Don't worry about whether you could grab it with your hands, just if you could raise something that heavy over your head.):							
...how limited are you doing this using BOTH ARMS?	1	2	3	4	5	6	7
THE FOLLOWING QUESTIONS ARE ABOUT YOUR ABILITY TO PULL AND PUSH WITH YOUR ARMS							
5. Think about pulling or sliding (without grasping) a light object such as a can of soda, that is on a table, towards you:							
...how limited are you doing this kind of thing using your RIGHT ARM?	1	2	3	4	5	6	7
...how limited are you doing this kind of thing using your LEFT ARM?	1	2	3	4	5	6	7
6. Think about pulling or sliding (without grasping) a heavy object (up to 10 lbs.), that is on a table, towards you:							
...how limited are you doing this kind of thing using your RIGHT ARM?	1	2	3	4	5	6	7
...how limited are you doing this kind of thing using your LEFT ARM?	1	2	3	4	5	6	7
7. Think about pushing a light object such as a can of soda on a table, away from you:							
...how limited are you doing this kind of thing using your RIGHT ARM?	1	2	3	4	5	6	7
...how limited are you doing this kind of thing using your LEFT ARM?	1	2	3	4	5	6	7
8. Think about pushing a heavy object (up to 10 lbs.) on a table, away from you:							
...how limited are you doing this kind of thing using your RIGHT ARM?	1	2	3	4	5	6	7
...how limited are you doing this kind of thing using your LEFT ARM?	1	2	3	4	5	6	7

	Totally Limited	Extremely Limited	Very Limited	Moderately Limited	Some Limitation	A little Limited	Not at all Limited
9. Think about pushing down with both arms into your chair enough to lift your buttocks (both sides) off the seat (do a push-up weight shift): how limited are you doing this?	1	2	3	4	5	6	7
THE FOLLOWING QUESTIONS ARE ABOUT MOVING AND POSITIONING YOUR ARM AND WRIST							
10. With your hand on your lap palm down, think about curling your wrist upwards, keeping your arm on your lap:							
...how limited are you doing this motion using your RIGHT HAND?	1	2	3	4	5	6	7
...how limited are you doing this motion using your LEFT HAND?	**1**	**2**	**3**	**4**	**5**	**6**	**7**
11. Think about turning your hand over - from your palm facing up to facing the floor, keeping your elbow bent at your side (the arm motion someone would make when turning a doorknob or a dial):							
...how limited are you doing this motion using your RIGHT ARM?	1	2	3	4	5	6	7
...how limited are you doing this motion using your LEFT ARM?	**1**	**2**	**3**	**4**	**5**	**6**	**7**
THE FOLLOWING QUESTIONS ARE ABOUT USING YOUR HANDS AND FINGERS							
12. Think about grasping and holding an object like a hammer with your hand:							
...how limited are you doing this kind of thing using your RIGHT HAND?	1	2	3	4	5	6	7
...how limited are you doing this kind of thing using your LEFT HAND?	**1**	**2**	**3**	**4**	**5**	**6**	**7**
13. Think about picking up a small object such as a paper clip or the cap of a tube of toothpaste with the tips of your thumb and first two fingers:							
...how limited are you doing this kind of thing using your RIGHT HAND?	1	2	3	4	5	6	7
...how limited are you doing this kind of thing using your LEFT HAND?	**1**	**2**	**3**	**4**	**5**	**6**	**7**

Name\ID: Date: Capabilities of Upper Extremity Instrument - CUE ™ V 1.1/ p4

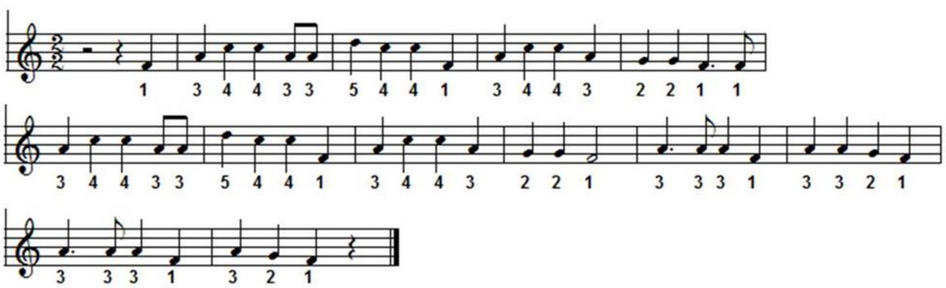
	Totally Limited	Extremely Limited	Very Limited	Moderately Limited	Some Limitation	A little Limited	Not at all Limited
14. Think about pinching and holding an object between your thumb and the side of your index finger, such as holding a key:							
...how limited are you doing this kind of thing using your RIGHT HAND?	1	2	3	4	5	6	7
...how limited are you doing this kind of thing using your LEFT HAND?	**1**	**2**	**3**	**4**	**5**	**6**	**7**
15. Think about grasping a large object like the lid of a 2 pound jar of mayonnaise with the tips of the fingers hard enough to pick the jar up or open the lid:							
...how limited are you doing this kind of thing using your RIGHT HAND?	1	2	3	4	5	6	7
...how limited are you doing this kind of thing using your LEFT HAND?	**1**	**2**	**3**	**4**	**5**	**6**	**7**
16. Think about using your fingers to manipulate objects, such as holding a coin and turning it over and over with your fingers:							
...how limited are you doing this kind of thing using your RIGHT HAND?	1	2	3	4	5	6	7
...how limited are you doing this kind of thing using your LEFT HAND?	**1**	**2**	**3**	**4**	**5**	**6**	**7**
17. Think about pressing something with the tip of your index finger (not knuckle) such as dialing a touch-tone phone or ringing a doorbell:							
...how limited are you doing this kind of thing using your RIGHT HAND?	1	2	3	4	5	6	7
...how limited are you doing this kind of thing using your LEFT HAND?	**1**	**2**	**3**	**4**	**5**	**6**	**7**

CUE™ v1.1 Form revised June 23, 2005

APPENDIX L

INITIAL SONGS

One More River



I Fed My Horse

Oh Susanna

Go To Sleepy

Christ was Born in Bethlehem

Old Rabbit

The Farmer's Boy

Turnip Greens

APPENDIX M

PASSIVE HAPTIC REHABILITATION PILOT STUDY POST QUESTIONNAIRE

MMT Passive Haptic Rehabilitation Study 2011 Post Questionnaire

Introduction:

Thank you for your participation in the Mobile Music Touch (MMT) project. Please complete this brief questionnaire about your experiences during the study.

There are no right or wrong answers. We are interested in your opinions and experiences. Your responses will be kept confidential.

INSTRUCTIONS:

Please read each question carefully and give the response that best fits with your experience. If you do not understand a question, please do not hesitate to ask for help.

Music practice sessions:

	Strongly Agree	Agree	Neither Agree nor Disagree	Disagree	Strongly Disagree
I enjoyed playing music.					
I may continue playing the piano after this study.					
I found this an interesting way to spend my time.					

Wearing the MMT glove:

	Strongly Agree	Agree	Neither Agree nor Disagree	Disagree	Strongly Disagree
I enjoyed wearing the glove.					
The vibration did not interfere with daily activities.					
The glove was uncomfortable.					
The glove interfered with my mobility.					
I found myself tapping along with the vibration.					
I was not embarrassed to be seen wearing the glove.					

Motor and Sensory Changes:

Have you noticed any changes in your ability to feel with your hands during this study?

(Y/N) ______________

If Yes, please explain: ____

____

____

____

Have you noticed any changes in your ability to perform daily activities with your hands during this study?

(Y/N) ______________

If Yes, please explain: ____

____

____

____

Wear of the MMT Glove:

Are there any activities that the glove interfered with? (Y/N) ______________

If Yes, please list: ____

____

If Yes, please indicate how it interfered:

____

____

Comment about your overall experience wearing the glove

Please tell us any issues concerning the glove (fit, wearibility, comfort, interference or assistance with day-to-day activities):

____

____

____

Please use the space below for any additional comments, suggestions or questions you have about your experience with the MMT glove or the music practice sessions.

Thank you for your participation

APPENDIX N

PASSIVE HAPTIC REHABILITATION POST QUESTIONNAIRE WITHOUT GLOVE

MMT Passive Haptic Rehabilitation Study 2011 Post Questionnaire v2

Introduction:

Thank you for your participation in the Mobile Music Touch (MMT) project. Please complete this brief questionnaire about your experiences during the study.

There are no right or wrong answers. We are interested in your opinions and experiences. Your responses will be kept confidential.

INSTRUCTIONS:

Please read each question carefully and give the response that best fits with your experience. If you do not understand a question, please do not hesitate to ask for help.

Music practice sessions:

	Strongly Agree	Agree	Neither Agree nor Disagree	Disagree	Strongly Disagree
I enjoyed playing music.					
I found playing piano too difficult.					
I found this an interesting way to spend my time.					
I don't feel as though I have learned a new skill.					
I'm happy about the improvement in my performance playing the piano.					
Playing music on the piano was relaxing.					
Playing the piano was boring.					
I enjoyed the challenge of learning to play piano.					
I found I could master the selected songs in one week.					
I'm disappointed about the lack of					

improvement in my performance playing the piano.					
I find that I can use my hand more effectively in daily tasks.					
I found learning to play the piano way too challenging.					
I find that I noticed an improvement in my ability to feel sensations with my hand.					
I did not notice any improvements in my ability to use my hands.					
I found my mood improved over the course of the study.					
I may continue playing the piano after this study.					
I have not noticed any change in my ability to feel with my hands.					
I found it too difficult to master a song in one week.					
I felt my mood did not improve over the course of the study.					
I felt like I was learning a new skill, not doing rehab.					

Motor and Sensory Changes:

Have you noticed any changes in your ability to feel with your hands during this study?

(Y/N) _______________

If Yes, please explain: ____

____

____

____

Have you noticed any changes in your ability to perform daily activities with your hands during this study?

(Y/N) ________________

If Yes, please explain: ____

____

____

____

Activities:

What other activities do you enjoy doing in your spare time (examples: video games, exercise, internet, gardening, etc…)? ____

____

I would pay _________ dollars for the MMT system. ($50, $200, $500, $2000, $10,000).

Please use the space below for any additional comments, suggestions or questions you have about your experience with the MMT glove or the music practice sessions.

____

____

____

Thank you for your participation

APPENDIX O

PASSIVE HAPTIC REHABILITATION POST QUESTIONNAIRE WITH GLOVE

MMT Passive Haptic Rehabilitation Study 2011 Post Questionnaire v1

Introduction:

Thank you for your participation in the Mobile Music Touch (MMT) project. Please complete this brief questionnaire about your experiences during the study.

There are no right or wrong answers. We are interested in your opinions and experiences. Your responses will be kept confidential.

INSTRUCTIONS:

Please read each question carefully and give the response that best fits with your experience. If you do not understand a question, please do not hesitate to ask for help.

Music practice sessions:

	Strongly Agree	Agree	Neither Agree nor Disagree	Disagree	Strongly Disagree
I enjoyed playing music.					
I found playing piano too difficult.					
I found this an interesting way to spend my time.					
I don’t feel as though I have learned a new skill.					
I'm happy about the improvement in my performance playing the piano.					
Playing music on the piano was relaxing.					
Playing the piano was boring.					

I enjoyed the challenge of learning to play piano.					
I found I could master the selected songs in one week.					
I'm disappointed about the lack of improvement in my performance playing the piano.					
I find that I can use my hand more effectively in daily tasks.					
I found learning to play the piano way too challenging.					
I find that I noticed an improvement in my ability to feel sensations with my hand.					
I did not notice any improvements in my ability to use my hands.					
I found my mood improved over the course of the study.					
I may continue playing the piano after this study.					
I have not noticed any change in my ability to feel with my hands.					
I believe the glove helped accelerate my learning of the songs.					
I found it too difficult to master a song in one week.					
I felt my mood did not					

improve over the course of the study.					
I felt like I was learning a new skill, not doing rehab.					

Wearing the MMT glove:

	Strongly Agree	Agree	Neither Agree nor Disagree	Disagree	Strongly Disagree
The glove was uncomfortable.					
The vibration did not interfere with daily activities.					
I enjoyed wearing the glove.					
The glove did not interfere with my daily activities.					
I found myself tapping along with the vibration.					
I was not embarrassed to be seen wearing the glove.					
The vibration interfered with my daily activities.					
The vibration was annoying.					
The vibration made me more aware of my fingers.					
The vibration made my fingers feel					

numb.					
The glove interfered with my daily activities.					
I was embarrassed to be seen wearing the glove.					
I could "hear" the song in my head as it vibrated on my hand.					

Motor and Sensory Changes:

Have you noticed any changes in your ability to feel with your hands during this study?

(Y/N) _______________

If Yes, please explain: ____

____

____

____

Have you noticed any changes in your ability to perform daily activities with your hands during this study?

(Y/N) _______________

If Yes, please explain: ____

____

____

____

Wear of the MMT Glove:

Are there any activities that the glove interfered with? (Y/N) _______________

If Yes, please list: ____

____

If Yes, please indicate how it interfered:

____

____

Activities:

What other activities do you enjoy doing in your spare time (examples: video games, exercise, internet, gardening, etc…)? ____

____

I would pay _________ dollars for the MMT system. ($50, $200, $500, $2000, $10,000).

Comment about your overall experience wearing the glove

Please tell us any issues concerning the glove (fit, wearibility, comfort, interference or assistance with day-to-day activities):

____

____

____

____

____

____

____

____

Please use the space below for any additional comments, suggestions or questions you have about your experience with the MMT glove or the music practice sessions.

____

____

____

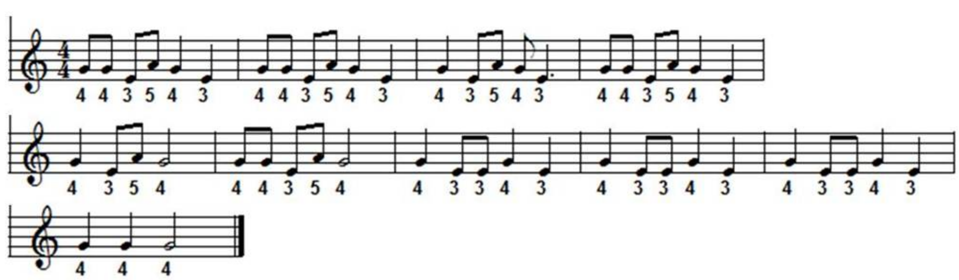
Thank you for your participation

APPENDIX P

SONGS, FULL STUDY

Ode to Joy

Mary Come a Running



Little Sally Ann

Marching Round the Fodder Stack

Old Dan Tucker

My Father’s House

Show Me the Way

I Hear the Train a Coming

Blow Ye Winds Blow

Joe Magerac

Night Herding

Dry Bones

The Gospel Train

River Go Down

Zekial Saw the Wheel

APPENDIX Q

SEMMES-WEINSTEIN CHANGES DEPICTED BY ON-HAND TESTING SITE FOR *WITHOUT GLOVE* CONDITION

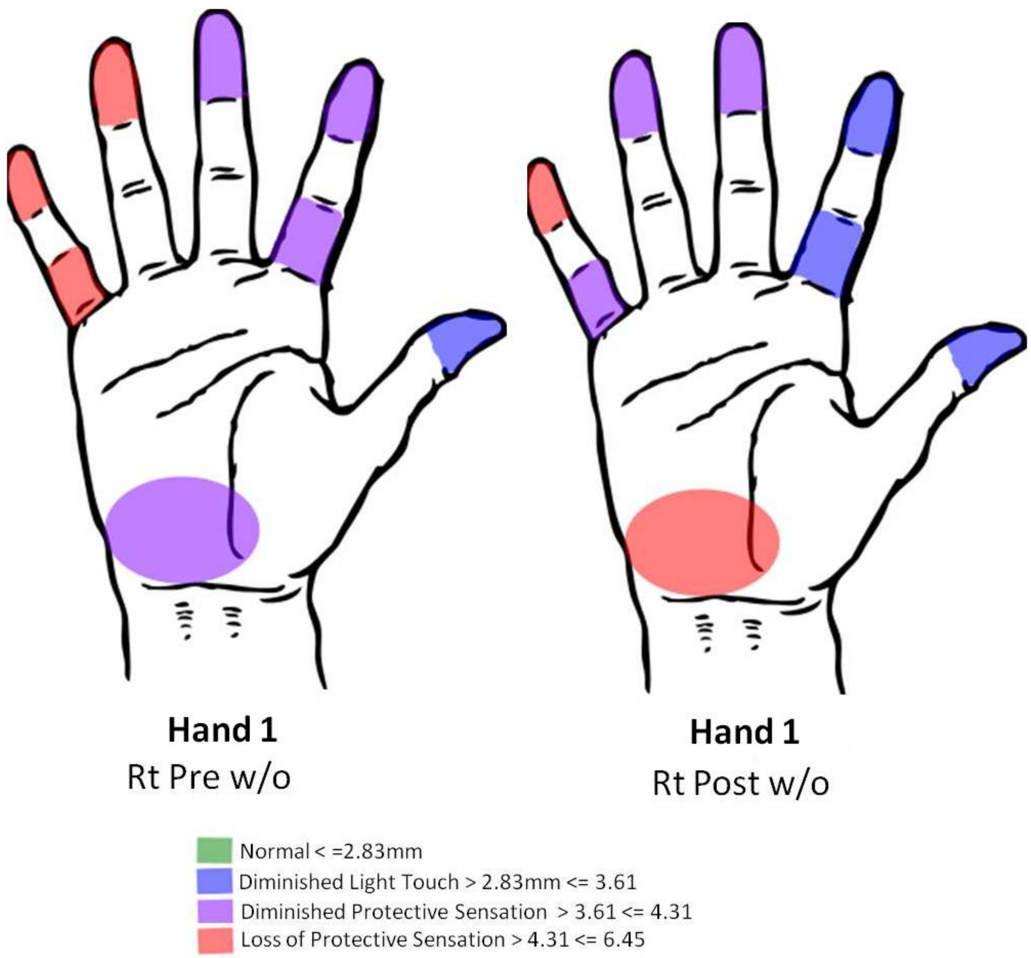


Figure 61: *Without Glove* Semmes-Weinstein Changes.

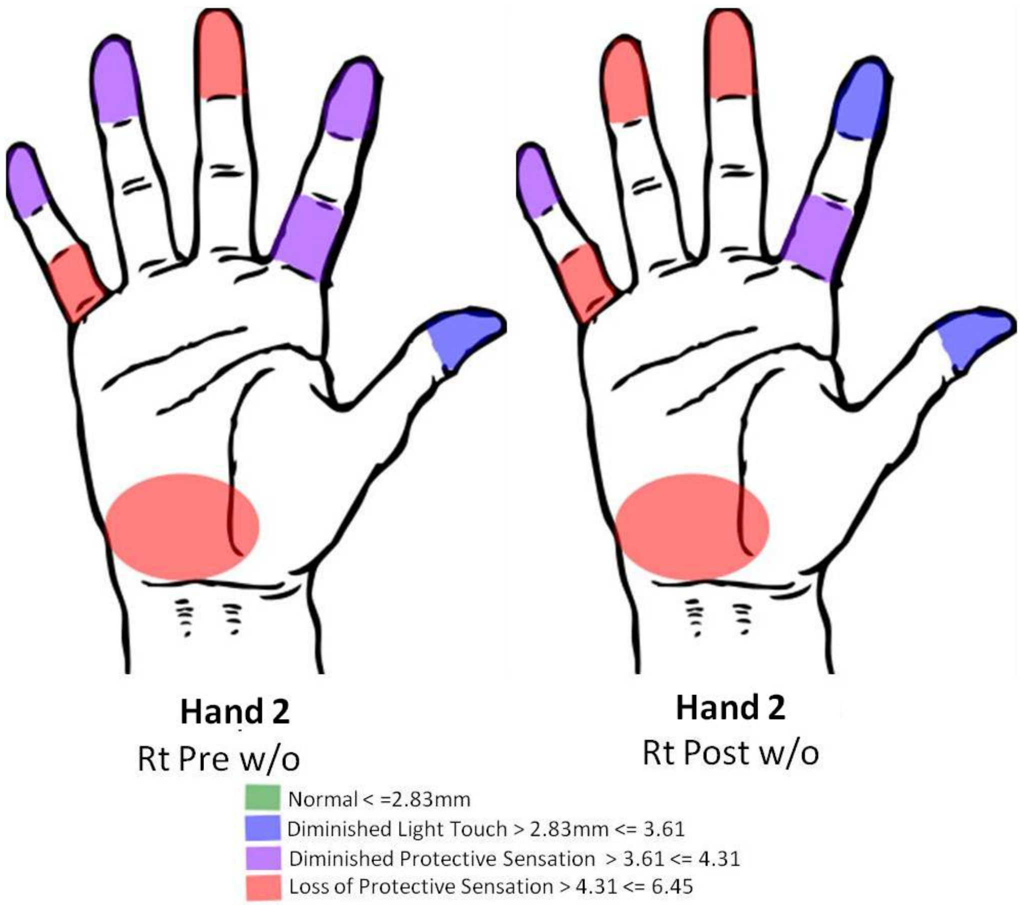


Figure 62: *Without Glove* Semmes-Weinstein Changes.

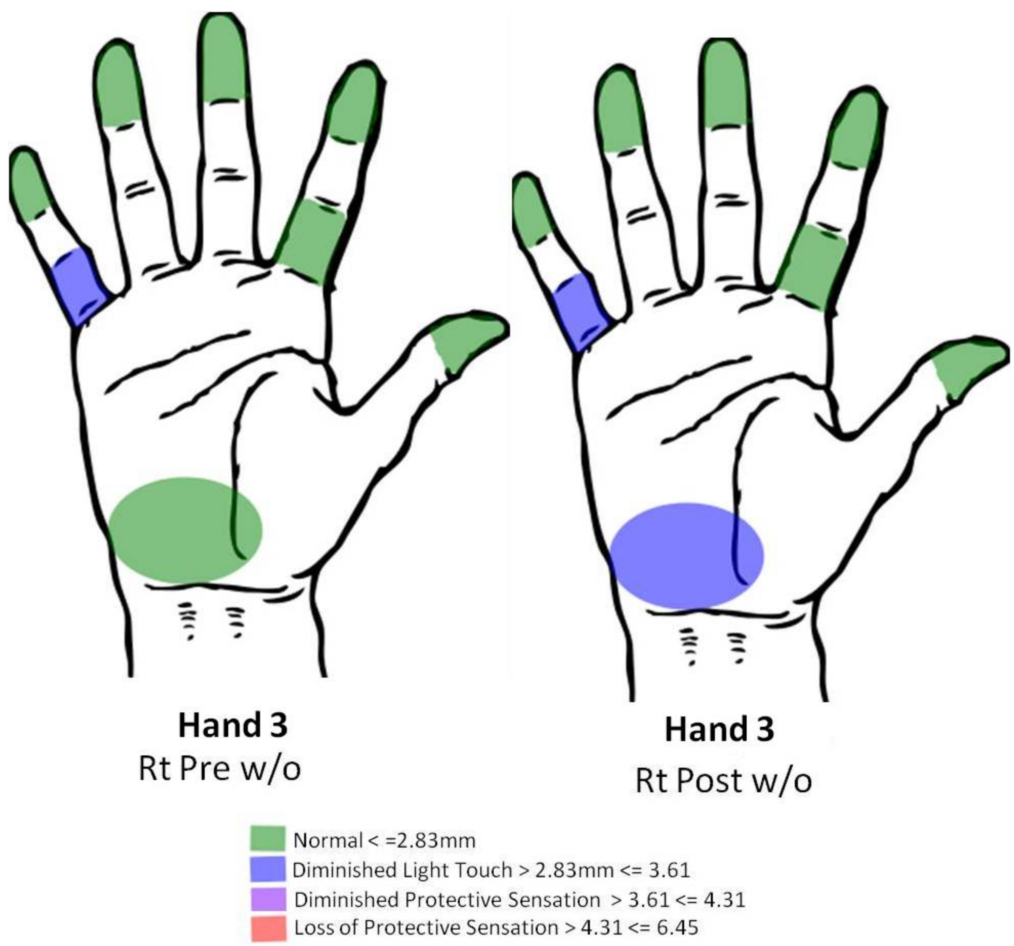


Figure 63: *Without Glove* Semmes-Weinstein Changes.

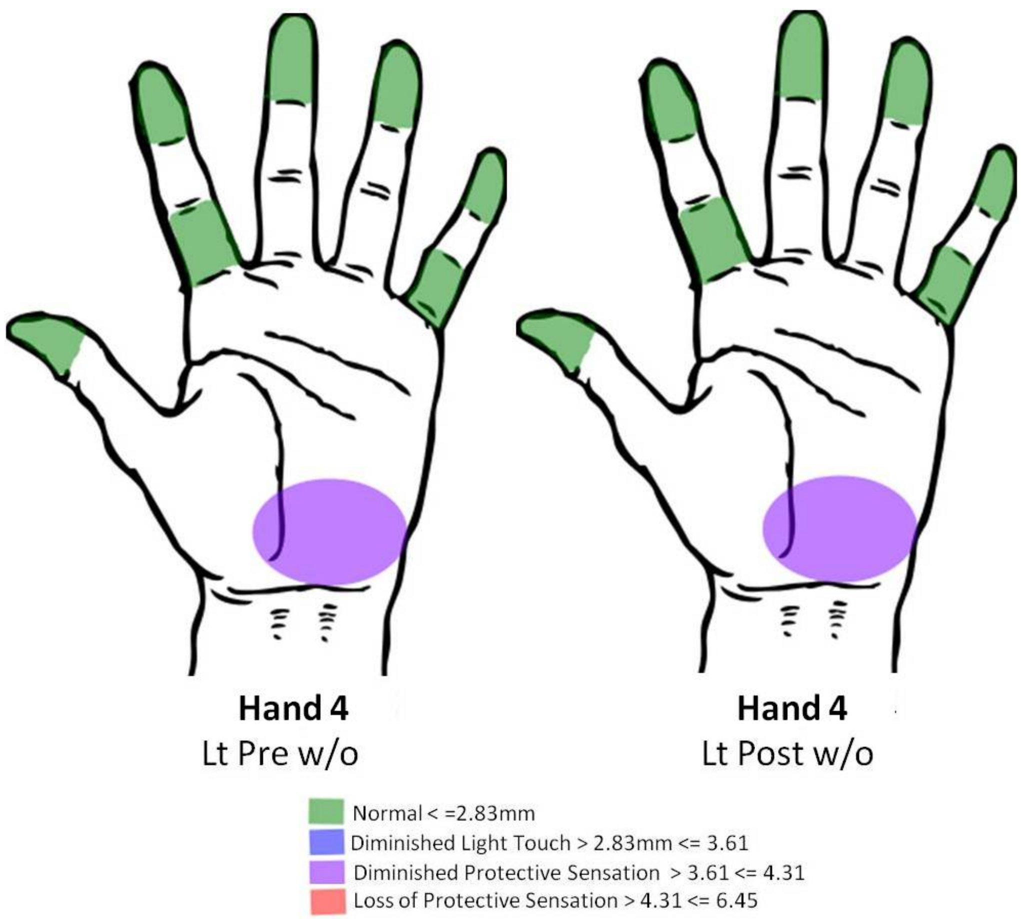


Figure 64: *Without Glove* Semmes-Weinstein Changes.

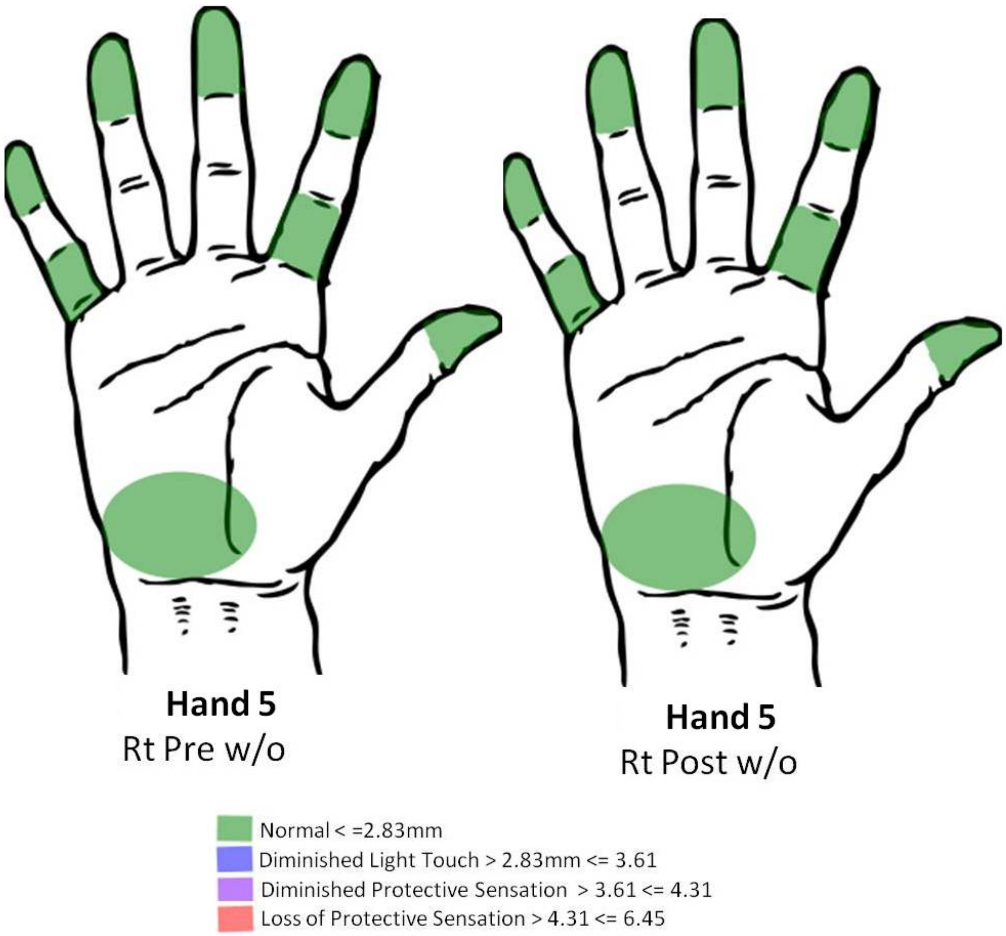


Figure 65: *Without Glove* Semmes-Weinstein Changes.

APPENDIX R

SEMMES-WEINSTEIN CHANGES DEPICTED BY ON-HAND TESTING SITE FOR *WITH GLOVE* CONDITION

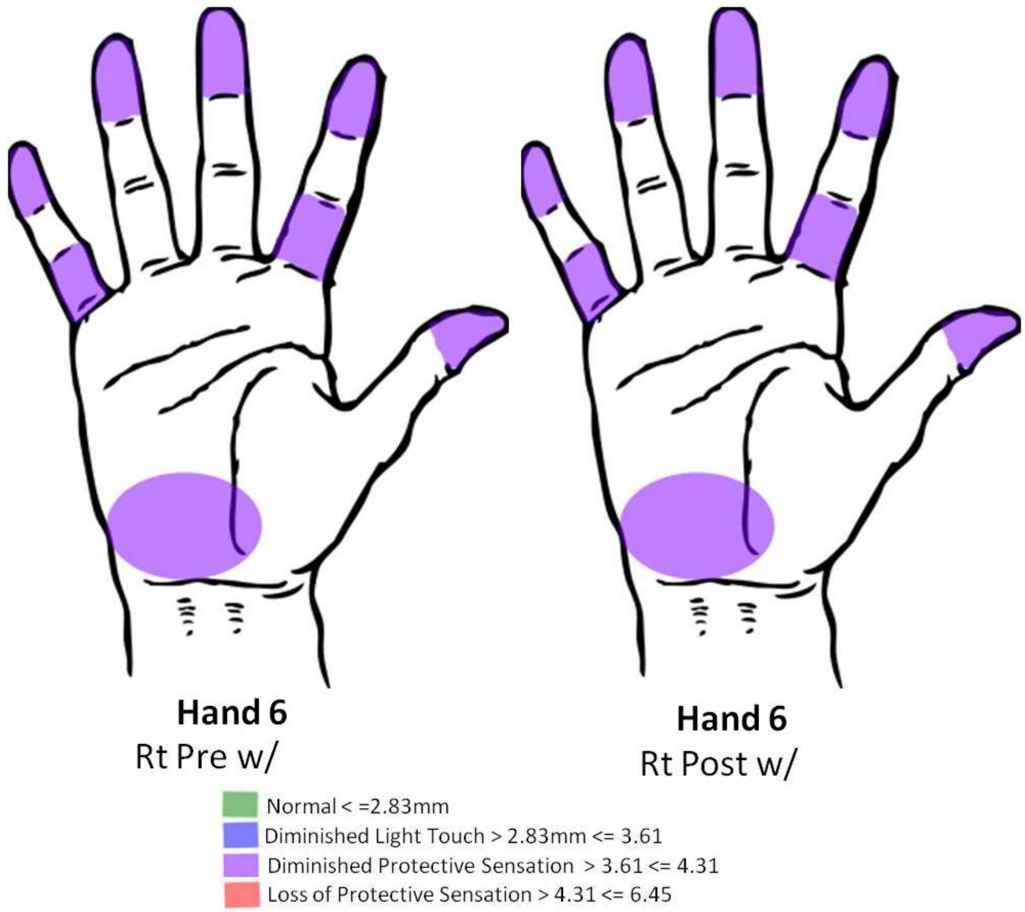


Figure 66: *With Glove* Semmes-Weinstein Changes.

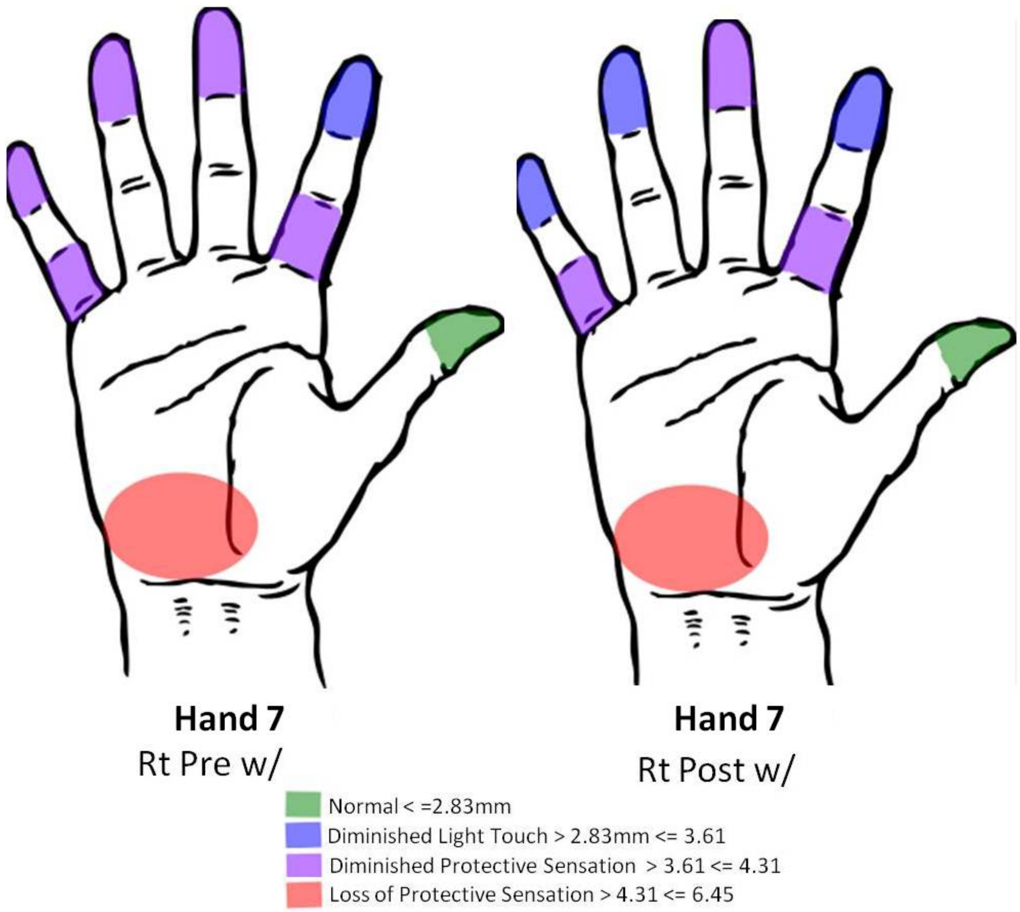


Figure 67: *With Glove* Semmes-Weinstein Changes.

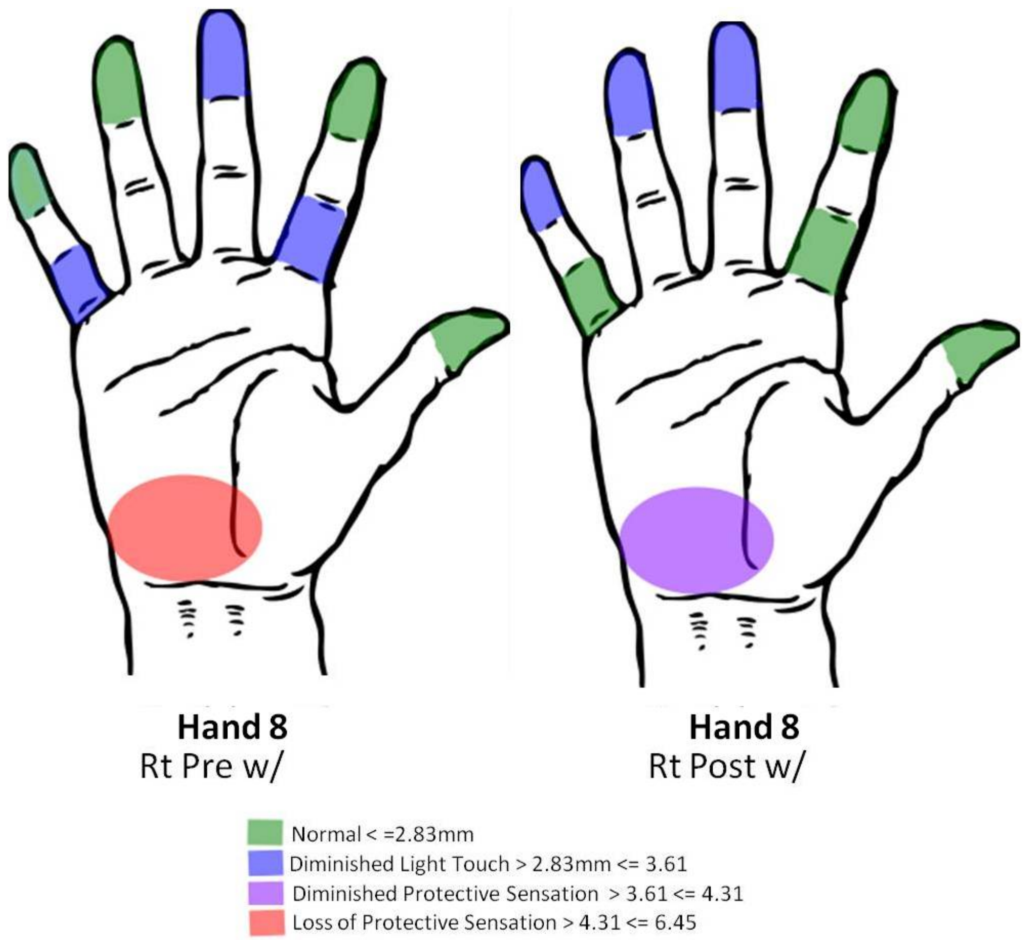


Figure 68: *With Glove* Semmes-Weinstein Changes.

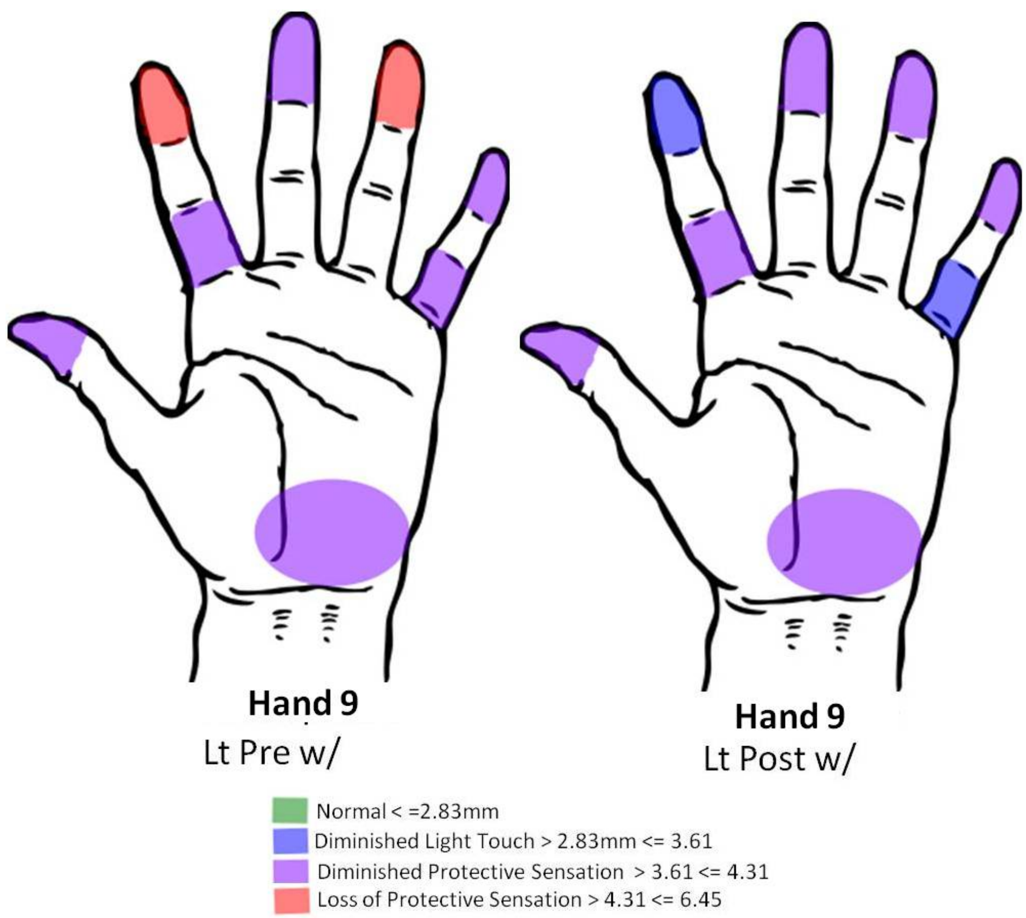


Figure 69: *With Glove* Semmes-Weinstein Changes.

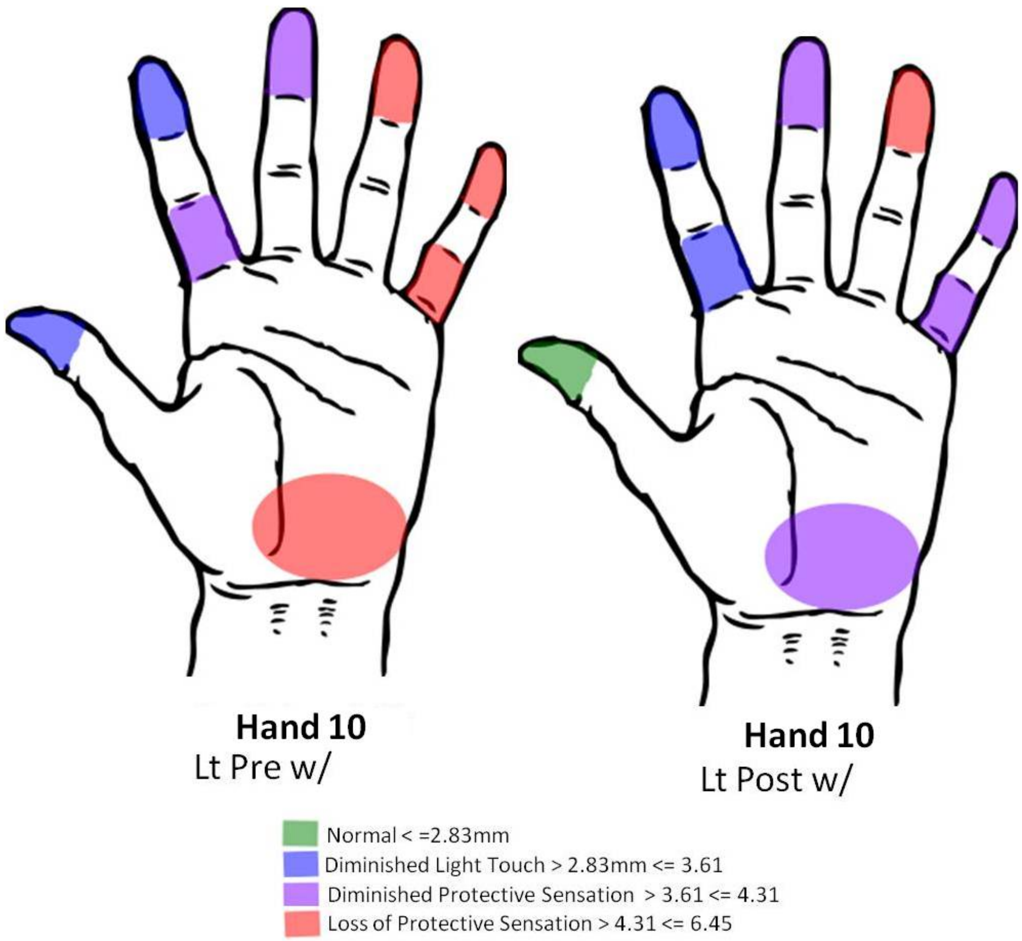


Figure 70: *With Glove* Semmes-Weinstein Changes.

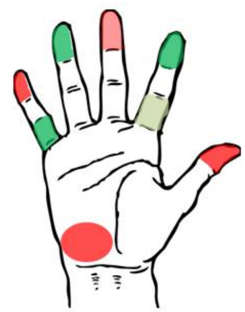
APPENDIX S

PHR STUDY HAND DATA SUMMARY SHEETS

Hand 1

Level injury: C6
Date Injury: 31 MAR 08

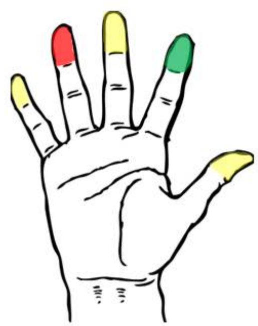
Semmes-Weinstein



- $\Delta \leq -0.35mm$
- $-0.35mm < \Delta < 0mm$
- $\Delta = 0mm$
- $0mm < \Delta < 0.35mm$
- $\Delta \geq 0.35mm$

	Pre	Mid	Post		% Chng
Thumb	3.22	2.83	3.61	0.39	12.11
Forefinger prox	3.84	3.61	3.61	-0.23	-5.99
Forefinger dist	4.31	3.61	3.84	-0.47	-10.90
Middle	4.17	4.08	4.31	0.14	3.36
Ring	4.74	5.07	4.31	-0.43	-9.07
Pinky prox	5.46	5.18	4.31	-1.15	-21.06
Pinky dist	5.46	4.17	5.88	0.42	7.69
Back Palm	3.84	5.46	5.18	1.34	34.90

2 pt Discriminator



- $\Delta \leq -2mm$
- $-2mm < \Delta < 0mm$
- $\Delta = 0mm$
- $0mm < \Delta < 2mm$
- $\Delta \geq 2mm$

2 pt Discriminator (Right hand only)					% Chng
Thumb	2	2	2	0	0.00
Forefinger	7	9	2	-5	-71.43
Middle	4	8	4	0	0.00
Ring	3	11	11	8	266.67
Pinky	20	20	20	0	0.00

AMES

Grasp Strength Test

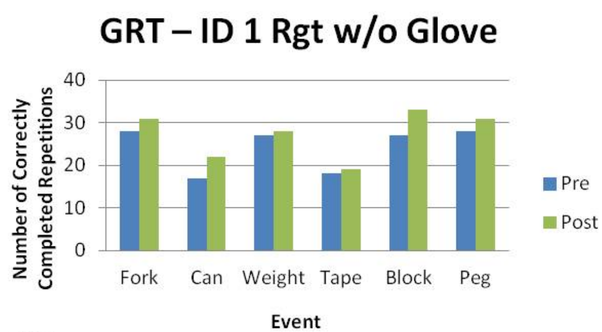
Extension			Flexion		
Pre	Mid	Post	Pre	Mid	Post
11	12.2	15.8	28	28.6	31.1
14	12.4	14.3	28	32.3	32.8
14	13.6	14.3	27	30.5	35.1

Wrist Strength Test

Right			Left		
Pre	Mid	Post	Pre	Mid	Post
37	55.5	49.7	47	77.8	95.6
43	44.7	47.3	54	89	93.5
39	45.5	57.7	58	77.5	95.9

JPGrasp			JPWrist		
Pre	Mid	Post	Pre	Mid	Post
294	401	398	494	321	421

Figure 71: Hand 1 Data Body Structures



ID 1 Right w/o Glove

	Pre			Mid			Post			Change	% Chng
Fork	29	1	28	30	0	30	31	0	31	3	10.71
Can	18	1	17	19	1	18	23	1	22	5	29.41
Weight	27	0	27	25	2	23	28	0	28	1	3.70
Tape	19	1	18	21	1	20	21	2	19	1	5.56
Block	28	1	27	29	0	29	33	0	33	6	22.22
Peg	28	0	28	31	0	31	31	0	31	3	10.71

ARAT

Grasp Subscale	Pre	Mid	Post
Block 10 cm	3	3	3
Block 2.5 cm	3	3	3
Block 5 cm	3	3	3
Block 7.5 cm	3	3	3
Cricket Ball	3	3	3
Sharp. Stone	3	3	3
	18	18	18

Grip Subscale	Pre	Mid	Post
Water pour	2	2	2
2.25 cm alloy	3	3	3
1 cm alloy	3	3	3
Washer bolt	3	3	3
	11	11	11

Pinch Subscale	Pre	Mid	Post
Ball brg (ring/thumb)	1	2	2
Marble (index/thumb)	3	3	3
Ball brg (middle/thumb)	2	3	3
Ball brg (index/thumb)	3	2	3
Marble (ring/thumb)	2	3	3
Marble (middle/thumb)	3	3	3
	14	16	17

Gross Movement Scale	Pre	Mid	Post
Hand behind head	3	3	3
Hand top head	3	3	3
Hand mouth	3	3	3
	9	9	9
Totals	52	54	55

* ARAT is out of 57

CUE

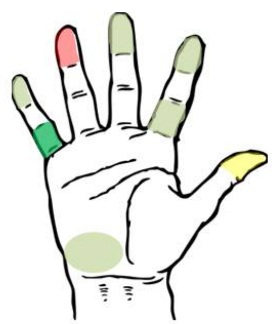
Subject ID	Hand	Glove	Pre Test				Post Test				Difference				
			CUE Total	CUE Both	CUE Right	CUE Left	CUE Total	CUE Both	CUE Right	CUE Left	Total	Both	Right	Left	Int. Hand
1	Right	w/o	188	14	90	84	175	14	81	80	-13	0	-9	-4	-9

Figure 72: Hand 1 Data Function & Participation

Semmes-Weinstein

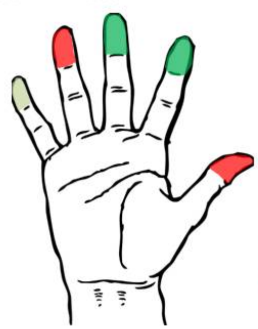
Hand 2

Level injury: C5
Date Injury: 18 JUL 2010



	Pre	Mid	Post		% Chng
Thumb	3.61	3.61	3.61	0	0.00
Forefinger prox	4.08	3.61	3.84	-0.24	-5.88
Forefinger dist	3.84	3.84	3.61	-0.23	-5.99
Middle	4.74	4.56	4.56	-0.18	-3.80
Ring	4.31	4.74	4.56	0.25	5.80
Pinky prox	5.18	4.74	4.56	-0.62	-11.97
Pinky dist	4.08	4.74	3.84	-0.24	-5.88
Back Palm	4.93	4.56	4.74	-0.19	-3.85

2 pt Discriminator



2 pt Discriminator (Right hand only)					% Chng
Thumb	8	2	14	6	75.00
Forefinger	20	8	8	-12	-60.00
Middle	20	12	9	-11	-55.00
Ring	12	15	14	2	16.67
Pinky	11	20	10	-1	-9.09

AMES

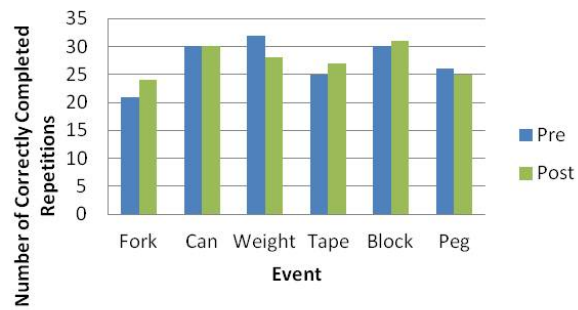
Extension			Flexion		
Pre	Mid	Post	Pre	Mid	Post
8.4	5.4	10.9	27.9	32.6	27.1
9	11.7	9.7	30.9	30.9	25.2
8.9	8.4	11.1	29.6	31	27.6

Right			Left		
Pre	Mid	Post	Pre	Mid	Post
33.3	26.8	32	49.5	55	45.3
30.6	25	32.1	54.7	54.5	43.9
30.5	48.2	31.3	60.4	52.6	40.1

JP Grasp		
Pre	Mid	Post
159	223	386

JP Wrist		
Pre	Mid	Post
405	438	321

Figure 73: Hand 2 Data Body Structures



ID 2 Right w/o Glove

Pre			Mid			Post			Change	% Chng
22	1	21	24	0	24	24	0	24	3	14.29
31	1	30	29	0	29	30	0	30	0	0.00
32	0	32	29	1	28	29	1	28	-4	-12.50
25	0	25	21	2	19	27	0	27	2	8.00
32	2	30	25	0	25	31	0	31	1	3.33
27	1	26	25	1	24	26	1	25	-1	-3.85

ARAT

Grasp Subscale	Pre	Mid	Post
Block 10 cm	3	3	3
Block 2.5 cm	3	3	3
Block 5 cm	3	3	3
Block 7.5 cm	3	3	3
Cricket Ball	3	3	3
Sharp. Stone	3	3	3
	18	18	18

Grip Subscale	Pre	Mid	Post
Water pour	2	2	2
2.25 cm alloy	3	3	3
1 cm alloy	3	3	2
Washer bolt	3	3	3
	11	11	10

Pinch Subscale	Pre	Mid	Post
Ball brg (ring/thumb)	3	3	3
Marble (index/thumb)	3	3	3
Ball brg (middle/thumb)	3	3	3
Ball brg (index/thumb)	3	3	3
Marble (ring/thumb)	3	3	3
Marble (middle/thumb)	3	3	3
	18	18	18

Gross Movement Scale	Pre	Mid	Post
Hand behind head	3	3	3
Hand top head	3	3	3
Hand mouth	3	3	3
	9	9	9
Totals	56	56	55

* ARAT is out of 57

CUE

Subject ID	Hand	Glove	Pre Test				Post Test				Difference				
			CUE Total	CUE Both	CUE Right	CUE Left	CUE Total	CUE Both	CUE Right	CUE Left	Total	Both	Right	Left	Int. Hand
2	Right	w/o	129	2	88	39	130	3	86	41	1	1	-2	2	-2

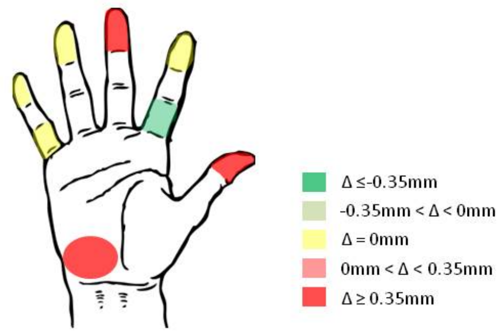
Figure 74: Hand 2 Data Function & Participation

Hand 3

Level injury: C3/C7

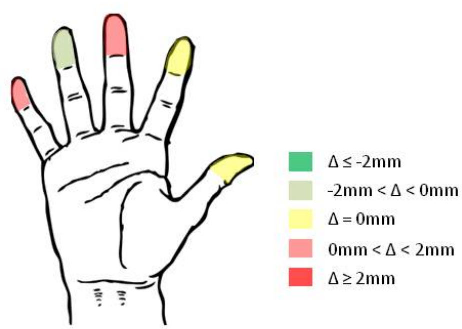
Date Injury: 18 MAY 2010

Semmes-Weinstein



	Pre	Mid	Post		% Chng
Thumb	2.44	2.83	2.83	0.39	15.98
Forefinger prox	2.83	2.83	2.44	-0.39	-13.78
Forefinger dist	2.83	2.83	2.83	0	0.00
Middle	2.44	2.44	2.83	0.39	15.98
Ring	2.83	2.83	2.83	0	0.00
Pinky prox	3.22	2.83	3.22	0	0.00
Pinky dist	2.83	2.83	2.83	0	0.00
Back Palm	2.83	2.83	3.22	0.39	13.78

2 pt Discriminator



2 pt Discriminator (Right hand only)				Change	% Chng
Thumb	3	3	3	0	0.00
Forefinger	3	3	3	0	0.00
Middle	2	4	3	1	50.00
Ring	4	3	3	-1	-25.00
Pinky	3	3	4	1	33.33

AMES

Grasp Strength Test

Extension			Flexion		
Pre	Mid	Post	Pre	Mid	Post
2.9	1.8	2.3	35.6	31	33.8
3.3	1.6	2.1	33.7	32.8	33.6
5	2.5	2.4	37.7	31.5	29.7

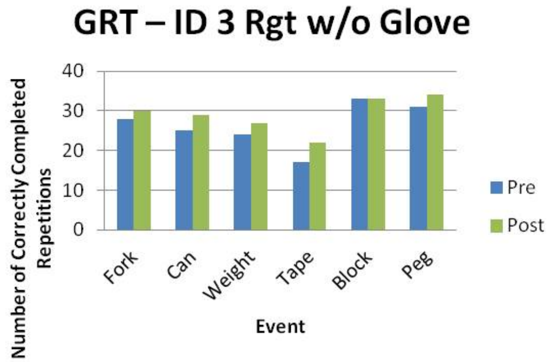
Wrist Strength Test

Right			Left		
Pre	Mid	Post	Pre	Mid	Post
11.2	23.8	16.5	27.1	47.6	46.3
10.5	25.8	19.1	36.4	42.4	43.9
11.1	23.1	20.1	40.3	44.9	42

Grasp Joint Pos			Wrist Joint Position		
Pre	Mid	Post	Pre	Mid	Post
105	102	90	307	414	447

Figure 75: Hand 3 Data Body Structures

ID 3 Right w/o Glove



Pre			Mid			Post			Change	% Chng
28	0	28	30	0	30	30	0	30	2	7.14
26	1	25	26	1	25	30	1	29	4	16.00
25	1	24	27	1	26	27	0	27	3	12.50
18	1	17	20	0	20	22	0	22	5	29.41
35	2	33	38	1	37	35	2	33	0	0.00
31	0	31	32	1	31	34	0	34	3	9.68

ARAT

Grasp Subscale	Pre	Mid	Post
Block 10 cm	2	2	2
Block 2.5 cm	3	3	3
Block 5 cm	3	3	3
Block 7.5 cm	2	3	2
Cricket Ball	3	3	3
Sharp. Stone	3	2	3
	16	16	16

Grip Subscale	Pre	Mid	Post
Water pour	3	3	3
2.25 cm alloy	3	3	3
1 cm alloy	2	3	3
Washer bolt	3	3	3
	11	12	12

Pinch Subscale	Pre	Mid	Post
Ball brg (ring/thumb)	2	2	0
Marble (index/thumb)	3	3	3
Ball brg (middle/thumb)	2	2	2
Ball brg (index/thumb)	2	3	3
Marble (ring/thumb)	2	2	3
Marble (middle/thumb)	2	3	3
	13	15	14

Gross Movement Scale	Pre	Mid	Post
Hand behind head	3	3	3
Hand top head	3	3	3
Hand mouth	3	3	3
	9	9	9
Totals	49	52	51

* ARAT is out of 57

CUE

Subject ID	Hand	Glove	Pre Test				Post Test				Difference				
			CUE Total	CUE Both	CUE Right	CUE Left	CUE Total	CUE Both	CUE Right	CUE Left	Total	Both	Right	Left	Int. Hand
3	Right	w/o	188	14	90	84	175	14	81	80	-13	0	-9	-4	-9

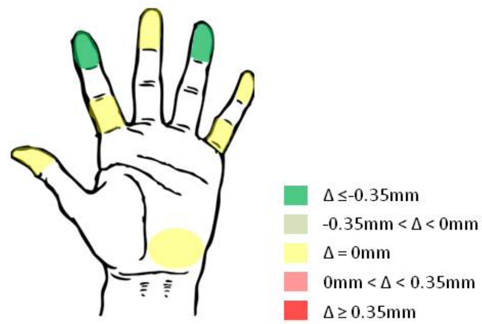
Figure 76: Hand 3 Data Function & Participation

Semmes-Weinstein

Hand 4

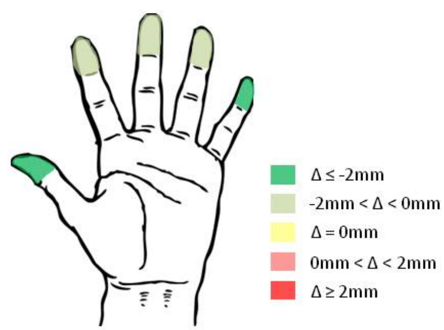
Level injury: C5/6

Date Injury: 25 MAY 2004



	Pre	Mid	Post		% Chng
Thumb	2.44	2.44	2.44	0	0.00
Forefinger prox	2.83	2.83	2.83	0	0.00
Forefinger dist	2.83	2.83	2.44	-0.39	-13.78
Middle	2.83	2.83	2.83	0	0.00
Ring	2.83	2.83	2.44	-0.39	-13.78
Pinky prox	2.83	2.83	2.83	0	0.00
Pinky dist	2.83	3.84	2.83	0	0.00
Back Palm	3.84	4.31	3.84	0	0.00

2 pt Discriminator



2 pt Discriminator (Left hand only)				Change	% Chng
Thumb	5	4	2	-3	-60.00
Forefinger	4	3	3	-1	-25.00
Middle	4	4	3	-1	-25.00
Ring	6	3	5	-1	-16.67
Pinky	10	5	5	-5	-50.00

AMES

Grasp Strength Test

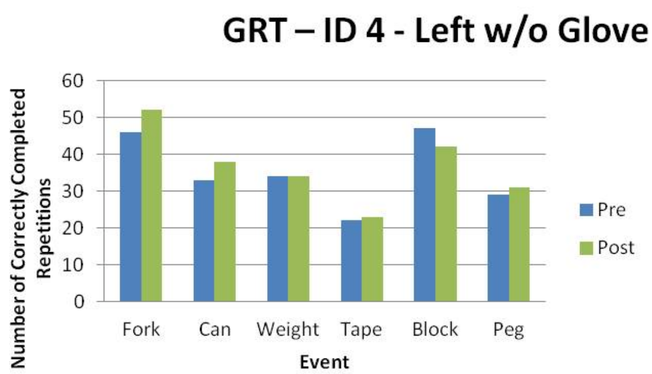
Extension			Flexion		
Pre	Mid	Post	Pre	Mid	Post
7.3	11	8.9	5.2	6.5	13.7
8.3	9	15.2	7.6	9	15.2
8.2	11.6	16.8	10	11.6	16.8

Wrist Strength Test

Right			Left		
Pre	Mid	Post	Pre	Mid	Post
134.3	139.9	152.6	66.7	51.3	112.6
140.5	144	156.1	132.3	79.6	108.5
137.7	145.3	154.9	105	95.7	113.2

Grasp Jt Pos			Wrist Jt Pos		
Pre	Mid	Post	Pre	Mid	Post
271	429	545	401	539	590

Figure 77: Hand 4 Data Body Structures



ID 4 Left w/o Glove

	Pre			Mid			Post			Change	% Chng
Fork	47	1	46	55	0	55	53	1	52	6	13.04
Can	33	0	33	35	0	35	39	1	38	5	15.15
Weight	35	1	34	38	0	38	37	3	34	0	0.00
Tape	24	2	22	25	0	25	25	2	23	1	4.55
Block	47	0	47	44	1	43	44	2	42	-5	-10.64
Peg	32	3	29	31	0	31	33	2	31	2	6.90

ARAT

Grasp Subscale	Pre	Mid	Post
Block 10 cm	3	3	3
Block 2.5 cm	3	3	3
Block 5 cm	3	3	3
Block 7.5 cm	3	3	3
Cricket Ball	3	3	3
Sharp. Stone	3	3	3
	18	18	18

Grip Subscale	Pre	Mid	Post
Water pour	3	3	3
2.25 cm alloy	3	3	3
1 cm alloy	3	3	3
Washer bolt	3	3	3
	12	12	12

Pinch Subscale	Pre	Mid	Post
Ball brg (ring/thumb)	3	2	3
Marble (index/thumb)	3	3	3
Ball brg (middle/thumb)	3	3	3
Ball brg (index/thumb)	2	1	2
Marble (ring/thumb)	3	3	3
Marble (middle/thumb)	3	3	3
	17	15	17

Gross Movement Scale	Pre	Mid	Post
Hand behind head	3	3	3
Hand top head	3	3	3
Hand mouth	3	3	3
	9	9	9
Totals	56	54	56

* ARAT is out of 57

CUE

Subject ID	Hand	Glove	Pre Test				Post Test				Difference				
			CUE Total	CUE Both	CUE Right	CUE Left	CUE Total	CUE Both	CUE Right	CUE Left	Total	Both	Right	Left	Int. Hand
4	Left	w/o	180	14	79	87	172	14	75	83	-8	0	-4	-4	-4

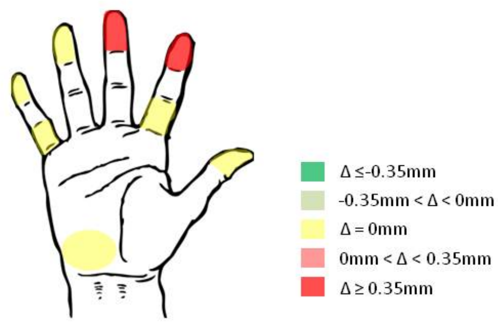
Figure 78: Hand 4 Data Function & Participation

Semmes-Weinstein

Hand 5

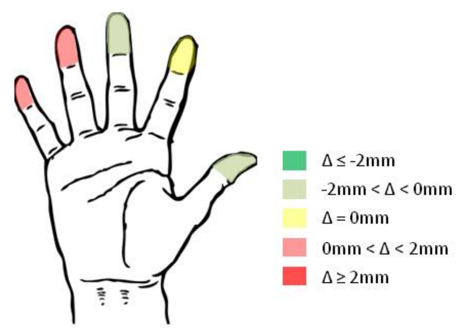
Level injury: C5

Date Injury: 10 AUG 2009



	Pre	Mid	Post	Change	% Chng
Thumb	2.44	2.44	2.44	0	0.00
Forefinger prox	2.44	2.44	2.44	0	0.00
Forefinger dist	2.36	2.44	2.83	0.47	19.92
Middle	2.44	2.44	2.83	0.39	15.98
Ring	2.44	2.36	2.44	0	0.00
Pinky prox	2.44	2.83	2.44	0	0.00
Pinky dist	2.44	2.44	2.44	0	0.00
Back Palm	2.83	2.44	2.83	0	0.00

2 pt Discriminator



2 pt Discriminator (Right hand only)				Change	% Chng
Thumb	4	3	3	-1	-25.00
Forefinger	3	2	3	0	0.00
Middle	4	3	3	-1	-25.00
Ring	2	3	3	1	50.00
Pinky	3	4	4	1	33.33

AMES

Grasp Strength Test

Extension			Flexion		
Pre	Mid	Post	Pre	Mid	Post
-2.1	4.1	1.3	34	27	33.1
-1.8	1.3	0.2	35.6	32.3	35
-1.3	2.1	0.4	31.3	30	34.1

Wrist Strength Test

Right			Left		
Pre	Mid	Post	Pre	Mid	Post
26	55.3	60.9	42.6	53.2	49.1
31.3	55.2	63.3	42.8	52.3	57.2
32.9	61.3	64.1	43	54.7	50.2

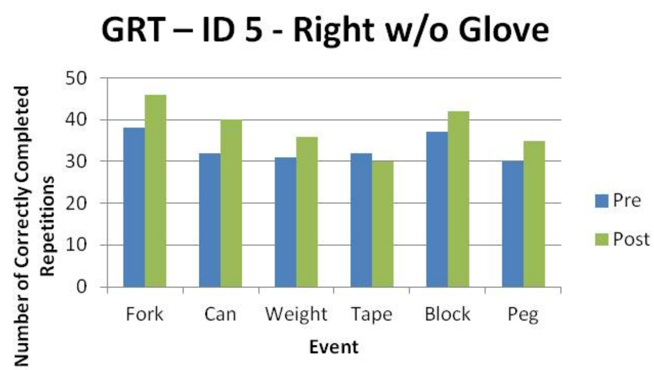
Grasp Jt Pos

Pre	Mid	Post
137	53	103

Wrist Jt. Pos

Pre	Mid	Post
421	533	557

Figure 79: Hand 5 Data Body Structures



ID 5 Right w/o Glove

	Pre			Mid			Post			Change	% Chng
Fork	38	0	38	43	0	43	46	0	46	8	21.05
Can	35	3	32	38	0	38	40	0	40	8	25.00
Weight	34	3	31	41	1	40	39	3	36	5	16.13
Tape	35	3	32	33	2	31	35	5	30	-2	-6.25
Block	40	3	37	48	1	47	43	1	42	5	13.51
Peg	33	3	30	33	2	31	35	0	35	5	16.67
										4.83333	
			200						229	3	

ARAT

Grasp Subscale	Pre	Mid	Post
Block 10 cm	3	3	3
Block 2.5 cm	3	3	3
Block 5 cm	3	3	3
Block 7.5 cm	3	3	3
Cricket Ball	3	3	3
Sharp. Stone	3	3	3

Grip Subscale	Pre	Mid	Post
Water pour	3	3	3
2.25 cm alloy	3	3	3
1 cm alloy	3	3	3
Washer bolt	3	3	3

Pinch Subscale	Pre	Mid	Post
Ball brg (ring/thumb)	0	1	2
Marble (index/thumb)	3	3	3
Ball brg (middle/thumb)	2	2	3
Ball brg (index/thumb)	3	3	3
Marble (ring/thumb)	2	2	2
Marble (middle/thumb)	3	3	3

Gross Movement Scale	Pre	Mid	Post
Hand behind head	3	3	3
Hand top head	3	3	3
Hand mouth	3	3	3
Totals	52	53	55

* ARAT is out of 57

CUE

Subject ID	Hand	Glove	Pre Test				Post Test				Difference				
			CUE Total	CUE Both	CUE Right	CUE Left	CUE Total	CUE Both	CUE Right	CUE Left	Total	Both	Right	Left	Int. Hand
5	Right	w/o	218	14	102	102	217	14	101	102	-1	0	-1	0	-1

Figure 80: Hand 5 Data Function & Participation

Semmes-Weinstein

Hand 6

Level injury: C3/C6

Date Injury: 16 APR 09

- Δ ≤ -0.35mm
- -0.35mm < Δ < 0mm
- Δ = 0mm
- 0mm < Δ < 0.35mm
- Δ ≥ 0.35mm

	Pre	Mid	Post		% Chng
Thumb	4.31	4.31	4.17	-0.14	-3.25
Forefinger prox	4.31	4.56	4.17	-0.14	-3.25
Forefinger dist	4.31	4.17	4.17	-0.14	-3.25
Middle	4.17	4.31	4.17	0	0.00
Ring	4.08	4.31	3.84	-0.24	-5.88
Pinky prox	4.31	4.56	4.31	0	0.00
Pinky dist	4.17	4.31	4.08	-0.09	-2.16
Back Palm	4.31	4.56	4.17	-0.14	-3.25

2 pt Discriminator

- Δ ≤ -2mm
- -2mm < Δ < 0mm
- Δ = 0mm
- 0mm < Δ < 2mm
- Δ ≥ 2mm

2 pt Discriminator (Right hand only)					% Chng
Thumb	12	8	7	-5	-41.67
Forefinger	4	3	3	-1	-25.00
Middle	2	2	2	0	0.00
Ring	2	2	3	1	50.00
Pinky	2	2	2	0	0.00

AMES

Grasp Strength Test

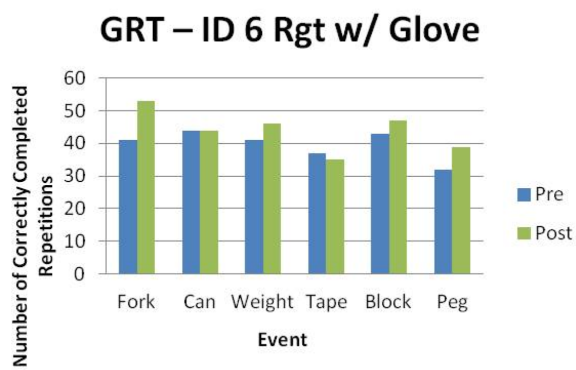
Extension			Flexion		
Pre	Mid	Post	Pre	Mid	Post
15	17.4	19.6	35	53.6	37.8
16	20.4	20.1	32	42.9	40.9
18	19.6	21.7	40	42.2	33.8

Wrist Strength Test

Right			Left		
Pre	Mid	Post	Pre	Mid	Post
65	84.1	77.6	78	59.8	69.2
58	81.8	87.2	55	55.8	115.7
58	79.2	83.6	77	71.1	103.1

JPGrasp			JPWrist		
Pre	Mid	Post	Pre	Mid	Post
524	614	597	433	405	547

Figure 81: Hand 6 Data Body Structures



ID 6 Right w/ Glove

Pre			Mid			Post				% Chng
42	1	41	51	0	51	53	0	53	12	29.27
44	0	44	42	3	39	45	1	44	0	0.00
44	3	41	45	1	44	46	0	46	5	12.20
38	1	37	37	2	35	37	2	35	-2	-5.41
44	1	43	50	1	49	47	0	47	4	9.30
34	2	32	38	2	36	39	0	39	7	21.88

ARAT

Grasp Subscale	Pre	Mid	Post
Block 10 cm	3	3	3
Block 2.5 cm	3	3	3
Block 5 cm	3	3	3
Block 7.5 cm	3	3	3
Cricket Ball	3	3	3
Sharp. Stone	3	3	3
	18	18	18

Grip Subscale	Pre	Mid	Post
Water pour	3	3	3
2.25 cm alloy	3	3	3
1 cm alloy	3	3	3
Washer bolt	3	3	3
	12	12	12

Pinch Subscale	Pre	Mid	Post
Ball brg (ring/thumb)	2	2	3
Marble (index/thumb)	3	3	3
Ball brg (middle/thumb)	3	2	3
Ball brg (index/thumb)	3	3	3
Marble (ring/thumb)	3	3	3
Marble (middle/thumb)	3	3	3
	17	16	18

Gross Movement Scale	Pre	Mid	Post
Hand behind head	3	3	3
Hand top head	3	3	3
Hand mouth	3	3	3
	9	9	9
Totals	56	55	57

* ARAT is out of 57

CUE

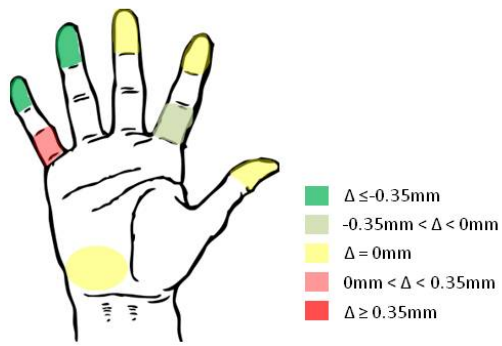
Subject ID	Hand	Glove	Pre Test				Post Test				Difference				
			CUE Total	CUE Both	CUE Right	CUE Left	CUE Total	CUE Both	CUE Right	CUE Left	Total	Both	Right	Left	Int. Hand
6	Right	with	145	10	100	35	139	6	103	30	-6	-4	3	-5	3

Figure 82: Hand 6 Data Function & Participation

Semmes-Weinstein

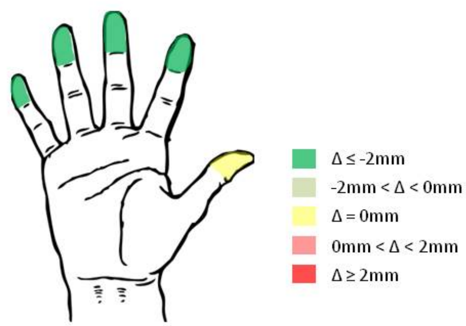
Hand 7

Level injury: C6/C7
Date Injury: 24 NOV 09



	Pre	Mid	Post		% Chng
Thumb	2.83	2.83	2.83	0	0.00
Forefinger prox	4.31	4.31	4.08	-0.23	-5.34
Forefinger dist	3.61	3.84	3.61	0	0.00
Middle	3.84	3.84	3.84	0	0.00
Ring	4.08	4.08	3.22	-0.86	-21.08
Pinky prox	3.84	4.08	4.08	0.24	6.25
Pinky dist	4.08	4.17	3.22	-0.86	-21.08
Back Palm	4.56	4.56	4.56	0	0.00

2 pt Discriminator



2 pt Discriminator (Right hand only)					% Chng
Thumb	3	2	3	0	0.00
Forefinger	13	6	2	-11	-84.62
Middle	15	13	2	-13	-86.67
Ring	15	14	7	-8	-53.33
Pinky	12	13	7	-5	-41.67

AMES

Grasp Strength Test

Extension			Flexion		
Pre	Mid	Post	Pre	Mid	Post
4	0.7	2.6	16	9.7	13.6
5	3.3	3.5	14	12.9	17.1
4	1.7	3.9	10	11.5	16.6

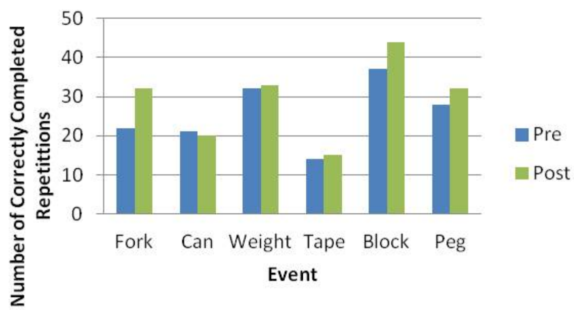
Wrist Strength Test

Right			Left		
Pre	Mid	Post	Pre	Mid	Post
-2	102.6	27.9	48	77.4	69.2
0	100.2	29.4	55	79.4	70.5
0	96.7	34.2	69	70	67.2

JPGrasp			JPWrist		
Pre	Mid	Post	Pre	Mid	Post
56	110	81	420	369	482

Figure 83: Hand 7 Data Body Structures

GRT – ID 7 Rgt w/ Glove



ID 7 Right w/ Glove

Pre			Mid			Post			Change	% Chng
23	1	22	32	0	32	32	0	32	10	45.45
22	1	21	24	4	20	21	1	20	-1	-4.76
32	0	32	36	2	34	35	2	33	1	3.13
16	2	14	20	4	16	18	3	15	1	7.14
38	1	37	40	3	37	44	0	44	7	18.92
30	2	28	34	0	34	33	1	32	4	14.29

ARAT

Grasp Subscale	Pre	Mid	Post
Block 10 cm	3	3	3
Block 2.5 cm	3	3	3
Block 5 cm	3	3	3
Block 7.5 cm	3	3	3
Cricket Ball	3	3	3
Sharp. Stone	3	3	3
	18	18	18

Grip Subscale	Pre	Mid	Post
Water pour	2	3	2
2.25 cm alloy	3	3	3
1 cm alloy	2	3	3
Washer bolt	3	3	3
	10	12	11

Pinch Subscale	Pre	Mid	Post
Ball brg (ring/thumb)	3	2	3
Marble (index/thumb)	3	3	3
Ball brg (middle/thumb)	2	3	3
Ball brg (index/thumb)	3	3	3
Marble (ring/thumb)	3	3	3
Marble (middle/thumb)	3	3	3
	17	17	18

Gross Movement Scale	Pre	Mid	Post
Hand behind head	3	3	3
Hand top head	3	3	3
Hand mouth	3	3	3
	9	9	9
Totals	54	56	56

* ARAT is out of 57

CUE

Subject ID	Hand	Glove	Pre Test				Post Test				Difference				
			CUE Total	CUE Both	CUE Right	CUE Left	CUE Total	CUE Both	CUE Right	CUE Left	Total	Both	Right	Left	Int. Hand
7	Right	with	201	14	99	88	212	14	103	95	11	0	4	7	4

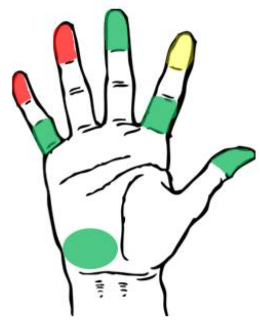
Figure 84: Hand 7 Data Function & Participation

Semmes-Weinstein

Hand 8

Level injury: C5/C6

Date Injury: 25 MAY 04



- Δ ≤ -0.35mm
- -0.35mm < Δ < 0mm
- Δ = 0mm
- 0mm < Δ < 0.35mm
- Δ ≥ 0.35mm

	Pre	Mid	Post		% Chng
Thumb	2.83	2.44	2.44	-0.39	-13.78
Forefinger prox	3.22	2.83	2.83	-0.39	-12.11
Forefinger dist	2.83	2.83	2.83	0	0.00
Middle	3.61	2.83	3.22	-0.39	-10.80
Ring	2.83	2.83	3.22	0.39	13.78
Pinky prox	3.61	3.61	2.83	-0.78	-21.61
Pinky dist	2.83	2.83	3.22	0.39	13.78
Back Palm	4.74	4.31	4.31	-0.43	-9.07

2 pt Discriminator

- Δ ≤ -2mm
- -2mm < Δ < 0mm
- Δ = 0mm
- 0mm < Δ < 2mm
- Δ ≥ 2mm

2 pt Discriminator (Right hand only)				Change	% Chng
Thumb	2	3	2	0	0.00
Forefinger	4	3	3	-1	-25.00
Middle	3	4	2	-1	-33.33
Ring	8	5	2	-6	-75.00
Pinky	20	7	4	-16	-80.00

AMES

Grasp Strength Test

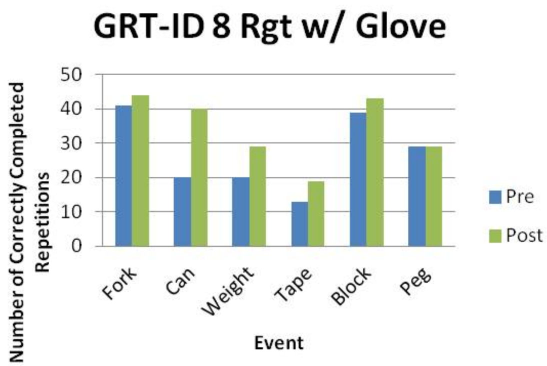
Extension			Flexion		
Pre	Mid	Post	Pre	Mid	Post
0.6	0.3	0.8	0.5	4	9.7
-0.3	0.6	0.7	-0.7	3.8	11.4
0.5	0.6	0.2	0.7	6.7	10

Wrist Strength Test

Right			Left		
Pre	Mid	Post	Pre	Mid	Post
58.9	79.8	81.4	45.6	60.6	84.5
63.2	91.5	94.3	48.8	68.9	80.2
59.9	82.1	87.6	46.1	73.1	74.6

JPGrasp			JPWrist		
Pre	Mid	Post	Pre	Mid	Post
70	74	78	442	531	448

Figure 85: Hand 8 Data Body Structures



ID 8 Rt w/ Glove

Pre			Mid			Post			Change	% Chng
41	0	41	48	1	47	45	1	44	3	7.32
21	1	20	29	2	27	40	0	40	20	100.00
23	3	20	29	4	25	32	3	29	9	45.00
15	2	13	15	3	12	19	0	19	6	46.15
40	1	39	43	1	42	44	1	43	4	10.26
32	3	29	30	2	28	31	2	29	0	0.00

ARAT

Grasp Subscale	Pre	Mid	Post
Block 10 cm	3	3	3
Block 2.5 cm	3	3	3
Block 5 cm	3	3	3
Block 7.5 cm	3	3	3
Cricket Ball	3	3	3
Sharp. Stone	3	3	3
	18	18	18

Grip Subscale	Pre	Mid	Post
Water pour	3	2	2
2.25 cm alloy	3	3	3
1 cm alloy	3	2	3
Washer bolt	2	3	2
	11	10	10

Pinch Subscale	Pre	Mid	Post
Ball brg (ring/thumb)	0	1	1
Marble (index/thumb)	2	2	3
Ball brg (middle/thumb)	0	1	1
Ball brg (index/thumb)	1	1	2
Marble (ring/thumb)	0	1	1
Marble (middle/thumb)	3	2	2
	6	8	10

Gross Movement Scale	Pre	Mid	Post
Hand behind head	3	3	3
Hand top head	3	3	3
Hand mouth	3	3	3
	9	9	9
Totals	44	45	47

* ARAT is out of 57

CUE

Subject ID	Hand	Glove	Pre Test				Post Test				Difference				
			CUE Total	CUE Both	CUE Right	CUE Left	CUE Total	CUE Both	CUE Right	CUE Left	Total	Both	Right	Left	Int. Hand
8	Right	with	177	14	80	83	180	14	79	87	3	0	-1	4	-1

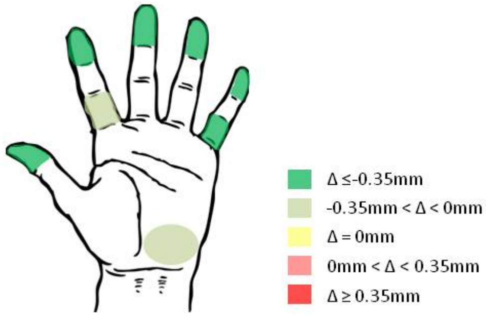
Figure 86: Hand 8 Data Function & Participation

Hand 9

Level injury: C5

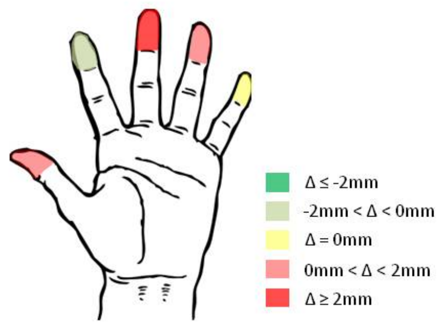
Date Injury: 18 JUL 2010

Semmes-Weinstein



	Pre	Mid	Post		% Chng
Thumb	4.31	4.08	3.84	-0.47	-10.90
Forefinger prox	4.31	4.08	4.08	-0.23	-5.34
Forefinger dist	4.74	4.08	3.61	-1.13	-23.84
Middle	4.31	4.17	3.84	-0.47	-10.90
Ring	4.56	4.17	3.84	-0.72	-15.79
Pinky prox	4.31	4.31	3.61	-0.7	-16.24
Pinky dist	4.17	4.08	3.84	-0.33	-7.91
Back Palm	4.31	4.31	4.17	-0.14	-3.25

2 pt Discriminator



2 pt Discriminator (Left Hand Glove)				Change	% Chng
Thumb	12	12	13	1	8.33
Forefinger	16	12	15	-1	-6.25
Middle	12	13	15	3	25.00
Ring	13	20	14	1	7.69
Pinky	13	14	13	0	0.00

AMES

*AMES Data not collected for mid-point on this participant

Grasp Strength Test

Extension			Flexion		
Pre	Mid	Post	Pre	Mid	Post
6		8.4	14.2		15.9
7.7		9.4	17.2		16.2
7.9		10	16.4		13.9

Wrist Strength Test

Right			Left		
Pre	Mid	Post	Pre	Mid	Post
43.7		43.4	17.5		8.1
45.5		40.6	18.9		16.8
50		39.6	20.5		18.8

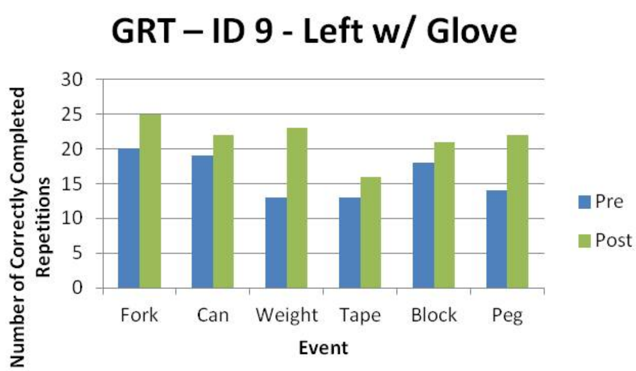
Hand Joint Pos Test

Pre	Mid	Post
291		247

Wrist Joint Pos Test

Pre	Mid	Post
361		395

Figure 87: Hand 9 Data Body Structures



ID 9 Left w/ Glove

	Pre			Mid			Post			Change	% Chng
Fork	20	0	20	20	0	20	25	0	25	5	25.00
Can	19	0	19	20	0	20	23	1	22	3	15.79
Weight	13	0	13	18	0	18	23	0	23	10	76.92
Tape	13	0	13	14	1	13	17	1	16	3	23.08
Block	18	0	18	23	0	23	21	0	21	3	16.67
Peg	15	1	14	20	0	20	22	0	22	8	57.14

ARAT

Grasp Subscale	Pre	Mid	Post
Block 10 cm	2	3	2
Block 2.5 cm	3	3	3
Block 5 cm	3	3	3
Block 7.5 cm	3	3	3
Cricket Ball	3	3	3
Sharp. Stone	3	3	3
	17	18	17

Grip Subscale	Pre	Mid	Post
Water pour	2	2	3
2.25 cm alloy	3	3	3
1 cm alloy	3	3	3
Washer bolt	3	2	3
	11	10	12

Pinch Subscale	Pre	Mid	Post
Ball brg (ring/thumb)	2	1	2
Marble (index/thumb)	3	3	3
Ball brg (middle/thumb)	2	2	2
Ball brg (index/thumb)	3	2	1
Marble (ring/thumb)	2	3	3
Marble (middle/thumb)	3	3	2
	15	14	13

Gross Movement Scale	Pre	Mid	Post
Hand behind head	1	2	2
Hand top head	1	2	3
Hand mouth	3	3	3
	5	7	8
Totals	48	49	50

* ARAT is out of 57

CUE

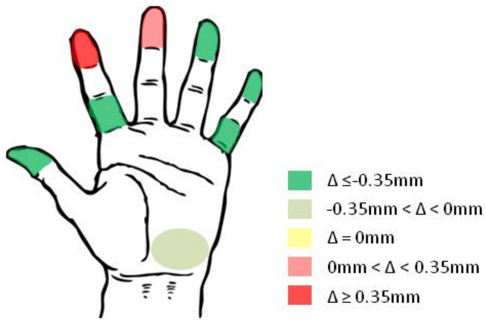
Subject ID	Hand	Glove	Pre Test				Post Test				Difference				
			CUE Total	CUE Both	CUE Right	CUE Left	CUE Total	CUE Both	CUE Right	CUE Left	Total	Both	Right	Left	Int. Hand
9	Left	with	124	3	77	44	142	6	82	54	18	3	5	10	10

Figure 88: Hand 9 Data Function & Participation

Semmes-Weinstein

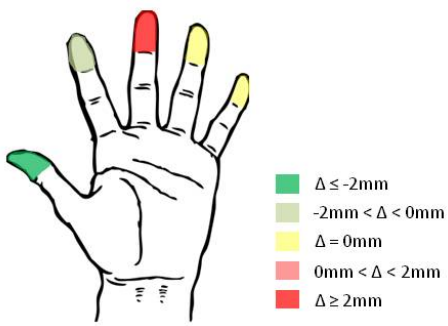
Hand 10

Level injury: C6
Date Injury: 31 MAR 2008



	Pre	Mid	Post		% Chng
Thumb	3.61	3.61	2.83	-0.78	-21.61
Forefinger prox	4.08	4.08	3.61	-0.47	-11.52
Forefinger dist	3.22	3.84	3.61	0.39	12.11
Middle	4.17	4.08	4.31	0.14	3.36
Ring	6.45	6.65	4.56	-1.89	-29.30
Pinky prox	5.88	5.07	4.31	-1.57	-26.70
Pinky dist	4.74	5.18	4.31	-0.43	-9.07
Back Palm	4.56	5.46	4.31	-0.25	-5.48

2 pt Discriminator



2 pt Discriminator				Change	% Chng
Thumb	4	2	2	-2	-50.00
Forefinger	4	2	3	-1	-25.00
Middle	13	20	15	2	15.38
Ring	20	20	20	0	0.00
Pinky	20	20	20	0	0.00

AMES

Grasp Strength Test

Extension			Flexion		
Pre	Mid	Post	Pre	Mid	Post
14.8	14.3	13.8	43.4	54.4	36.2
15	15.8	14.1	44.7	49.8	42.4
14.1	17.1	16.2	44.4	48.4	43.4

Wrist Strength Test

Right			Left		
Pre	Mid	Post	Pre	Mid	Post
68.7	112.2	110.9	47.4	55.3	60.5
86.4	98.5	110.9	46.9	57.2	64.3
102.6	116.7	117.9	48.4	59	61.7

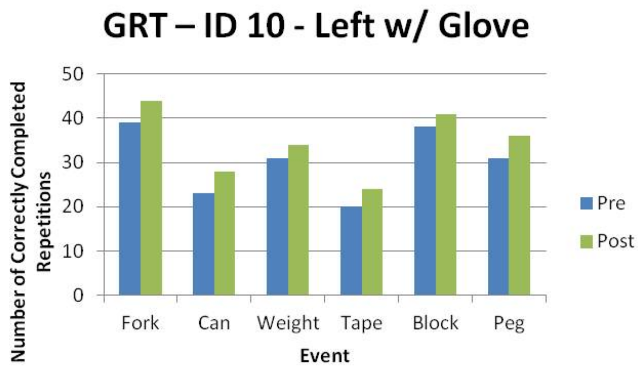
Grasp Joint Pos Test

Pre	Mid	Post
380	321	475

Wrist Joint Pos Test

Pre	Mid	Post
546	462	519

Figure 89: Hand 10 Data Body Structures



ID 10 Left w/ Glove

	Pre			Mid			Post			Change	% Chng
Fork	39	0	39	39	0	39	44	0	44	5	12.82
Can	24	1	23	27	0	27	29	1	28	5	21.74
Weight	31	0	31	34	0	34	34	0	34	3	9.68
Tape	21	1	20	24	0	24	25	1	24	4	20.00
Block	38	0	38	42	1	41	42	1	41	3	7.89
Peg	31	0	31	36	2	34	36	0	36	5	16.13

ARAT

Grasp Subscale	Pre	Mid	Post
Block 10 cm	3	3	3
Block 2.5 cm	3	3	3
Block 5 cm	3	3	3
Block 7.5 cm	3	3	3
Cricket Ball	3	3	3
Sharp. Stone	3	3	3
	18	18	18

Grip Subscale	Pre	Mid	Post
Water pour	3	3	3
2.25 cm alloy	3	3	3
1 cm alloy	3	3	3
Washer bolt	3	3	3
	12	12	12

Pinch Subscale	Pre	Mid	Post
Ball brg (ring/thumb)	0	2	1
Marble (index/thumb)	3	3	3
Ball brg (middle/thumb)	3	3	3
Ball brg (index/thumb)	3	3	3
Marble (ring/thumb)	3	2	3
Marble (middle/thumb)	3	3	3
	15	16	16

Gross Movement Scale	Pre	Mid	Post
Hand behind head	3	3	3
Hand top head	3	3	3
Hand mouth	3	3	3
	9	9	9
Totals	54	55	55

* ARAT is out of 57

CUE

Subject ID	Hand	Glove	Pre Test				Post Test				Difference				
			CUE Total	CUE Both	CUE Right	CUE Left	CUE Total	CUE Both	CUE Right	CUE Left	Total	Both	Right	Left	Int. Hand
10	Left	with	164	12	74	78	156	11	72	73	-8	-1	-2	-5	-5

Figure 90: Hand 10 Data Function & Participation

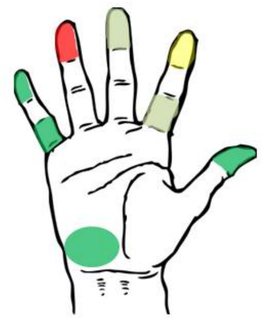
APPENDIX T

PHR STUDY HAND WITHIN SUBJECT DATA SUMMARY SHEETS

Hand 1 Within Subject

Level injury: C6
Date Injury: 31 MAR 08

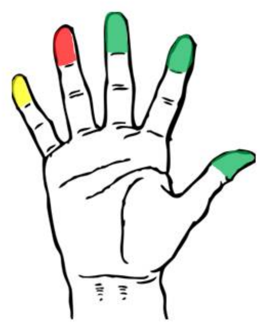
Semmes-Weinstein



- $\Delta \le -0.35mm$
- $-0.35mm < \Delta < 0mm$
- $\Delta = 0mm$
- $0mm < \Delta < 0.35mm$
- $\Delta \ge 0.35mm$

	Pre	Mid	Post		% Chng
Thumb	3.61	2.83	2.83	-0.78	-21.61
Forefinger prox	3.84	3.61	3.61	-0.23	-5.99
Forefinger dist	3.61	3.22	3.61	0	0.00
Middle	4.31	4.08	4.08	-0.23	-5.34
Ring	4.17	4.74	4.93	0.76	18.23
Pinky prox	4.93	4.56	4.56	-0.37	-7.51
Pinky dist	5.46	4.74	4.56	-0.9	-16.48
Back Palm	5.46	5.07	4.31	-1.15	-21.06
	4.42375	4.10625	4.06125	-0.3625	

2 pt Discriminator



- $\Delta \le -2mm$
- $-2mm < \Delta < 0mm$
- $\Delta = 0mm$
- $0mm < \Delta < 2mm$
- $\Delta \ge 2mm$

2 pt Discriminator (Right hand only)				Change	% Chng
Thumb	5	3	2	-3	-60.00
Forefinger	5	4	2	-3	-60.00
Middle	15	12	4	-11	-73.33
Ring	15	20	20	5	33.33
Pinky	20	20	20	0	0.00

AMES

Grasp Strength Test

Extension			Flexion		
Pre	Mid	Post	Pre	Mid	Post
14.8	12.3	19.5	33.5	31	39
16.4	13.6	15	31.9	30.7	36.6
16.3	15.3	13.8	30.8	33.7	35.5

Wrist Strength Test

Right			Left		
Pre	Mid	Post	Pre	Mid	Post
34.8	42	65.4	74.3	94.3	99.4
40.1	47	59.8	82.1	78.8	95.5
46.3	48.9	61.5	82.1	77.8	110

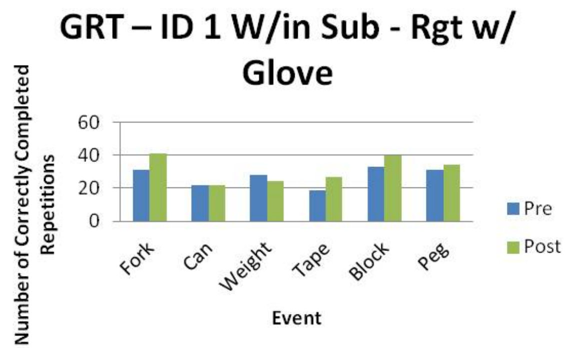
Grasp Joint Pos Test

Pre	Mid	Post
483	513	456

Wrist Joint Pos Test

Pre	Mid	Post
518	425	370

Figure 91: Hand 1 Within Subject Data Body Structures



ID 1 W/in Sub
Right w/o Glove

	Pre			Mid			Post			Change	% Chng
Fork	31	0	31	36	0	36	41	0	41	10	32.26
Can	23	1	22	24	0	24	23	1	22	0	0.00
Weight	28	0	28	27	1	26	27	3	24	-4	-14.29
Tape	21	2	19	22	1	21	27	0	27	8	42.11
Block	33	0	33	37	0	37	40	0	40	7	21.21
Peg	31	0	31	33	0	33	35	1	34	3	9.68

ARAT

Grasp Subscale	Pre	Mid	Post
Block 10 cm	3	3	3
Block 2.5 cm	3	3	3
Block 5 cm	3	3	3
Block 7.5 cm	3	3	3
Cricket Ball	3	3	3
Sharp. Stone	3	3	3
	18	18	18

Grip Subscale	Pre	Mid	Post
Water pour	2	2	2
2.25 cm alloy	3	3	3
1 cm alloy	3	3	3
Washer bolt	3	3	3
	11	11	11

Pinch Subscale	Pre	Mid	Post
Ball brg (ring/thumb)	2	0	0
Marble (index/thumb)	3	3	3
Ball brg (middle/thumb)	3	2	3
Ball brg (index/thumb)	3	3	3
Marble (ring/thumb)	3	3	3
Marble (middle/thumb)	3	3	3
	17	14	15

Gross Movement Scale	Pre	Mid	Post
Hand behind head	3	3	3
Hand top head	3	3	3
Hand mouth	3	3	3
	9	9	9
Totals	20	55	52

* ARAT is out of 57

CUE

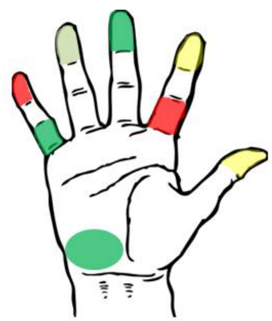
Subject ID	Hand	Glove	Pre Test				Post Test				Difference				
			CUE Total	CUE Both	CUE Right	CUE Left	CUE Total	CUE Both	CUE Right	CUE Left	Total	Both	Right	Left	Int. Hand
SM13	Right	with	171	10	81	80	164	12	74	78	-7	2	-7	-2	-7

Figure 92: Hand 1 Within Subject Data Function & Participation

Hand 2 Within Subject

Level injury: C5
Date Injury: 18 JUL 2010

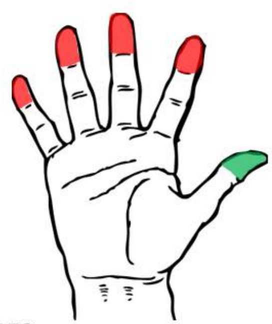
Semmes-Weinstein



- Δ ≤ -0.35mm
- -0.35mm < Δ < 0mm
- Δ = 0mm
- 0mm < Δ < 0.35mm
- Δ ≥ 0.35mm

	Pre	Mid	Post		% Chng
Thumb	3.61	3.22	3.61	0	0.00
Forefinger prox	3.84	3.84	4.17	0.33	8.59
Forefinger dist	3.61	4.08	3.61	0	0.00
Middle	4.56	4.31	3.84	-0.72	-15.79
Ring	4.56	4.74	4.31	-0.25	-5.48
Pinky prox	4.56	4.56	4.08	-0.48	-10.53
Pinky dist	3.84	4.56	4.31	0.47	12.24
Back Palm	4.74	4.31	4.08	-0.66	-13.92
	4.165	4.2025	4.00125	-0.16375	

2 pt Discriminator



- Δ ≤ -2mm
- -2mm < Δ < 0mm
- Δ = 0mm
- 0mm < Δ < 2mm
- Δ ≥ 2mm

2 pt Discriminator (Right hand glove)				Change	% Chng
Thumb	14	6	8	-6	-42.86
Forefinger	8	7	13	5	62.50
Middle	9	14	15	6	66.67
Ring	14	12	20	6	42.86
Pinky	10	12	15	5	50.00

AMES

Grasp Strength Test

Extension			Flexion		
Pre	Mid	Post	Pre	Mid	Post
10.9	6.9	5.9	27.1	25.5	22.4
9.7	8.9	6.8	25.2	26.3	22.2
11.1	10.3	6.7	27.6	27.5	23

Wrist Strength Test

Right			Left		
Pre	Mid	Post	Pre	Mid	Post
32	43.7	39	45.3	50.5	59.5
32.1	47.3	49.5	43.9	46	61.1
31.3	50.2	54.2	40.1	47.4	56.9

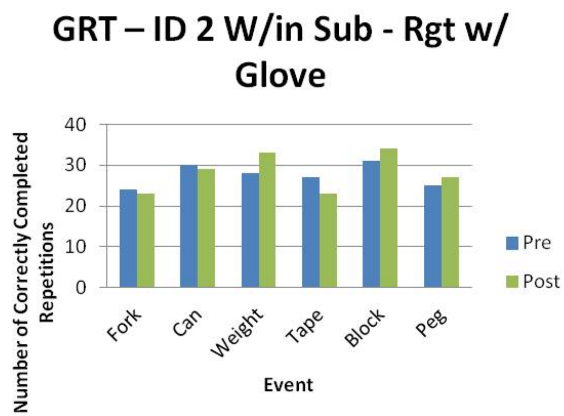
Hand Joint Pos Test

Pre	Mid	Post
386	219	265

Wrist Joint Pos Test

Pre	Mid	Post
321	399	278

Figure 93: Hand 2 Within Subject Data Body Structures



ID 2 Right w/o Glove

	Pre			Mid			Post			Change	% Chng
Fork	24	0	24	26	0	26	24	1	23	-1	-4.17
Can	30	0	30	29	0	29	29	0	29	-1	-3.33
Weight	29	1	28	29	2	27	33	0	33	5	17.86
Tape	27	0	27	25	0	25	24	1	23	-4	-14.81
Block	31	0	31	25	2	23	34	0	34	3	9.68
Peg	26	1	25	28	0	28	27	0	27	2	8.00

ARAT

Grasp Subscale	Pre	Mid	Post
Block 10 cm	3	3	3
Block 2.5 cm	3	3	3
Block 5 cm	3	3	3
Block 7.5 cm	3	3	3
Cricket Ball	3	3	3
Sharp. Stone	3	3	3
	18	18	18

Grip Subscale	Pre	Mid	Post
Water pour	2	3	3
2.25 cm alloy	3	3	3
1 cm alloy	2	3	3
Washer bolt	3	3	3
	10	12	12

Pinch Subscale	Pre	Mid	Post
Ball brg (ring/thumb)	3	3	3
Marble (index/thumb)	3	3	3
Ball brg (middle/thumb)	3	3	3
Ball brg (index/thumb)	3	3	3
Marble (ring/thumb)	3	3	3
Marble (middle/thumb)	3	3	3
	18	18	18

Gross Movement Scale	Pre	Mid	Post
Hand behind head	3	3	3
Hand top head	3	3	3
Hand mouth	3	3	3
	9	9	9
Totals	55	57	57

* ARAT is out of 57

CUE

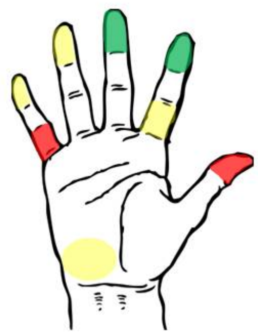
Subject ID	Hand	Glove	Pre Test				Post Test				Difference				
			CUE Total	CUE Both	CUE Right	CUE Left	CUE Total	CUE Both	CUE Right	CUE Left	Total	Both	Right	Left	Int. Hand
OX22	Right	with	130	3	86	41	124	3	77	44	-6	0	-9	3	-9

Figure 94: Hand 2 Within Subject Data Function & Participation

Hand 3 Within Subject

Level injury: C3/C7
Date Injury: 18 MAY 2010

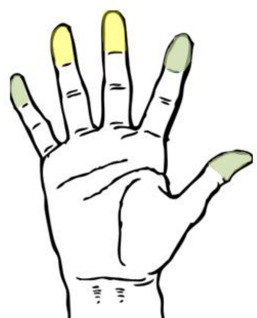
Semmes-Weinstein



- $\Delta \leq -0.35mm$
- $-0.35mm < \Delta < 0mm$
- $\Delta = 0mm$
- $0mm < \Delta < 0.35mm$
- $\Delta \geq 0.35mm$

	Pre	Mid	Post	
Thumb	2.83	2.44	2.44	-0.39
Forefinger prox	2.44	2.44	2.44	0
Forefinger dist	2.83	2.44	2.83	-0.39
Middle	2.83	2.44	2.44	-0.39
Ring	2.83	2.83	2.44	0
Pinky prox	3.22	3.61	3.22	0.39
Pinky dist	2.83	2.83	2.83	0
Back Palm	3.22	3.22	2.83	0
	2.87875	2.78125	2.68375	-0.0975

2 pt Discriminator



- $\Delta \leq -2mm$
- $-2mm < \Delta < 0mm$
- $\Delta = 0mm$
- $0mm < \Delta < 2mm$
- $\Delta \geq 2mm$

2 pt Discriminator (Right hand glove)				Average
Thumb	3	2	2	-1
Forefinger	3	2	2	-1
Middle	3	2	3	0
Ring	3	4	3	0
Pinky	4	2	3	-1
				-0.6

AMES

Grasp Strength Test

Extension			Flexion		
Pre	Mid	Post	Pre	Mid	Post
2.3	3.8	2.9	33.8	32.6	33.6
2.1	4.4	3.9	33.6	36	35.6
2.4	4.3	5.7	29.7	33.4	35.2

Wrist Strength Test

Right			Left		
Pre	Mid	Post	Pre	Mid	Post
16.5	19.1	21.4	46.3	46.6	48.7
19.1	20.5	21.8	43.9	44.1	51.1
20.1	21.6	24.4	42	43.2	50.2

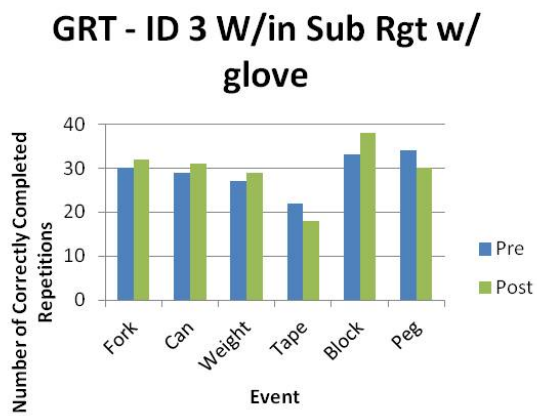
Grasp Jt Pos

Pre	Mid	Post
90	127	200

Wrist Jt. Pos

Pre	Mid	Post
447	468	486

Figure 95: Hand 3 Within Subject Data Body Structures



ID 3 Right w/in Sub Glove

	Pre			Mid			Post			Change	% Change
Fork	30	0	30	35	0	35	34	2	32	2	6.67
Can	30	1	29	29	3	26	33	2	31	2	6.90
Weight	27	0	27	28	0	28	31	2	29	2	7.41
Tape	22	0	22	25	1	24	24	6	18	-4	-18.18
Block	35	2	33	36	1	35	41	3	38	5	15.15
Peg	34	0	34	35	0	35	32	2	30	-4	-11.76

ARAT

Grasp Subscale	Pre	Mid	Post
Block 10 cm	2	3	2
Block 2.5 cm	3	3	3
Block 5 cm	3	3	3
Block 7.5 cm	2	3	3
Cricket Ball	3	3	3
Sharp. Stone	3	3	3
	16	18	17

Grip Subscale	Pre	Mid	Post
Water pour	3	3	3
2.25 cm alloy	3	3	3
1 cm alloy	2	3	3
Washer bolt	3	3	3
	11	12	12

Pinch Subscale	Pre	Mid	Post
Ball brg (ring/thumb)	0	0	1
Marble (index/thumb)	3	3	3
Ball brg (middle/thumb)	2	0	2
Ball brg (index/thumb)	3	3	3
Marble (ring/thumb)	3	2	3
Marble (middle/thumb)	3	3	3
	14	11	15

Gross Movement Scale	Pre	Mid	Post
Hand behind head	3	3	2
Hand top head	3	1	2
Hand mouth	3	3	3
	9	7	7
Totals	50	48	51

* ARAT is out of 57

CUE

Subject ID	Hand	Glove	Pre Test				Post Test				Difference				
			CUE Total	CUE Both	CUE Right	CUE Left	CUE Total	CUE Both	CUE Right	CUE Left	Total	Both	Right	Left	Int. Hand
TN21	Right	with	95	2	78	15	100	2	81	17	5	0	3	2	3

Figure 96: Hand 3 Within Subject Data Function & Participation

Semmes-Weinstein

Hand 4 Within Subject

Level injury: C5/6
Date Injury: 25 MAY 2004

- Δ ≤ -0.35mm
- -0.35mm < Δ < 0mm
- Δ = 0mm
- 0mm < Δ < 0.35mm
- Δ ≥ 0.35mm

	Pre	Mid	Post	Change	% Change
Thumb	2.44	1.65	2.36	-0.79	-32.38
Forefinger prox	2.83	2.83	2.83	0	0.00
Forefinger dist	2.44	2.44	2.44	0	0.00
Middle	2.83	2.44	2.44	-0.39	-13.78
Ring	2.44	2.83	2.44	0.39	15.98
Pinky prox	2.83	2.83	2.83	0	0.00
Pinky dist	2.83	2.44	2.83	-0.39	-13.78
Back Palm	3.84	2.83	3.61	-1.01	-26.30

2 pt Discriminator

AMES

- Δ ≤ -2mm
- -2mm < Δ < 0mm
- Δ = 0mm
- 0mm < Δ < 2mm
- Δ ≥ 2mm

2 pt Discriminator				Change	% Change
Thumb	2	4	5	3	150.00
Forefinger	3	3	2	-1	-33.33
Middle	3	4	2	-1	-33.33
Ring	5	3	3	-2	-40.00
Pinky	5	5	2	-3	-60.00

Grasp Strength Test

Extension			Flexion		
Pre	Mid	Post	Pre	Mid	Post
8.9	12	18.5	13.7	20.5	19.8
15.2	13.5	15.3	15.2	24	25.6
16.8	13.8	17.7	16.8	26.1	19

Wrist Strength Test

Right			Left		
Pre	Mid	Post	Pre	Mid	Post
152.6	99	147.4	112.6	79.9	109.9
156.1	138.7	157.2	108.5	91	117.2
154.9	148.1	149.4	113.2	85.3	135.8

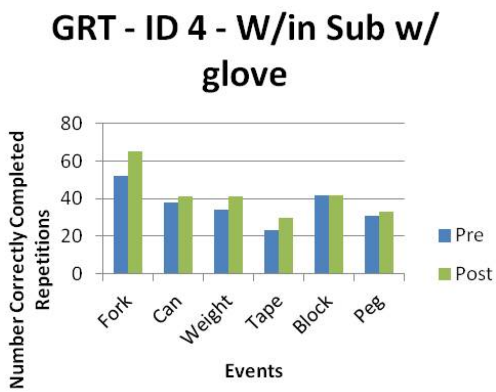
Grasp Jt. Pos

Pre	Mid	Post
545	533	445

Wrist Jt. Pos

Pre	Mid	Post
590	719	621

Figure 97: Hand 4 Within Subject Data Body Structures



ID 4 W/in Sub Left w/ Glove

Pre			Mid			Post			Change	% Change
53	1	52	51	0	51	65	0	65	13	25.00
39	1	38	40	0	40	41	0	41	3	7.89
37	3	34	33	2	31	41	0	41	7	20.59
25	2	23	26	0	26	31	1	30	7	30.43
44	2	42	45	0	45	44	2	42	0	0.00
33	2	31	31	3	28	33	0	33	2	6.45

ARAT

Grasp Subscale	Pre	Mid	Post
Block 10 cm	3	3	3
Block 2.5 cm	3	3	3
Block 5 cm	3	3	3
Block 7.5 cm	3	3	3
Cricket Ball	3	3	3
Sharp. Stone	3	3	3
	18	18	18

Grip Subscale	Pre	Mid	Post
Water pour	3	3	3
2.25 cm alloy	3	3	3
1 cm alloy	3	3	3
Washer bolt	3	3	3
	12	12	12

Pinch Subscale	Pre	Mid	Post
Ball brg (ring/thumb)	3	2	3
Marble (index/thumb)	3	3	3
Ball brg (middle/thumb)	3	3	3
Ball brg (index/thumb)	2	2	2
Marble (ring/thumb)	3	3	3
Marble (middle/thumb)	3	3	3
	17	16	17

Gross Movement Scale	Pre	Mid	Post
Hand behind head	3	3	3
Hand top head	3	3	3
Hand mouth	3	3	3
	9	9	9
Totals	56	55	56

* ARAT is out of 57

CUE

Subject ID	Hand	Glove	Pre Test				Post Test				Difference				
			CUE Total	CUE Both	CUE Right	CUE Left	CUE Total	CUE Both	CUE Right	CUE Left	Total	Both	Right	Left	Int. Hand
UL12	Left	with	172	14	75	83	180	14	78	88	8	0	3	5	5

Figure 98: Hand 4 Within Subject Data Function & Participation

APPENDIX U

MMT SYSTEM USAGE DATA

Table 29: MMT system glove usage data.

ID	Total minutes of usage	Average minutes of usage
1	981	24.5
2	2427	60.7
3	5327	113.2
4	3578	89.5
6	7983	199.6
7	4308	107.7
8	2882	72.1
9	2820	70.5
10	259	6.5
Avg	3396	85

APPENDIX V

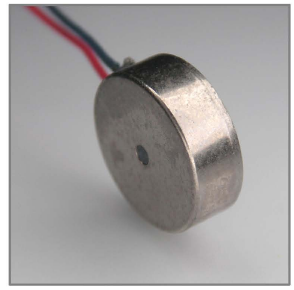
PRECISION MICRODRIVES VIBRATION MOTOR #310-101 DATASHEET

PRECISION MICRODRIVES™

310-101

10mm Shaftless Vibration Motor
3.4mm Button Type

Specification	Value
Voltage [V]	3
Frame Diameter [mm]	10
Body Length [mm]	3.4
Weight [g]	1.2
Voltage Range [V]	2.5~3.8
Rated Speed [rpm]	12000
Rated Current [mA]	75
Start Voltage [V]	2.3
Start Current [mA]	85
Terminal Resistance [Ohm]	75
Vibration Amplitude [G]	0.8



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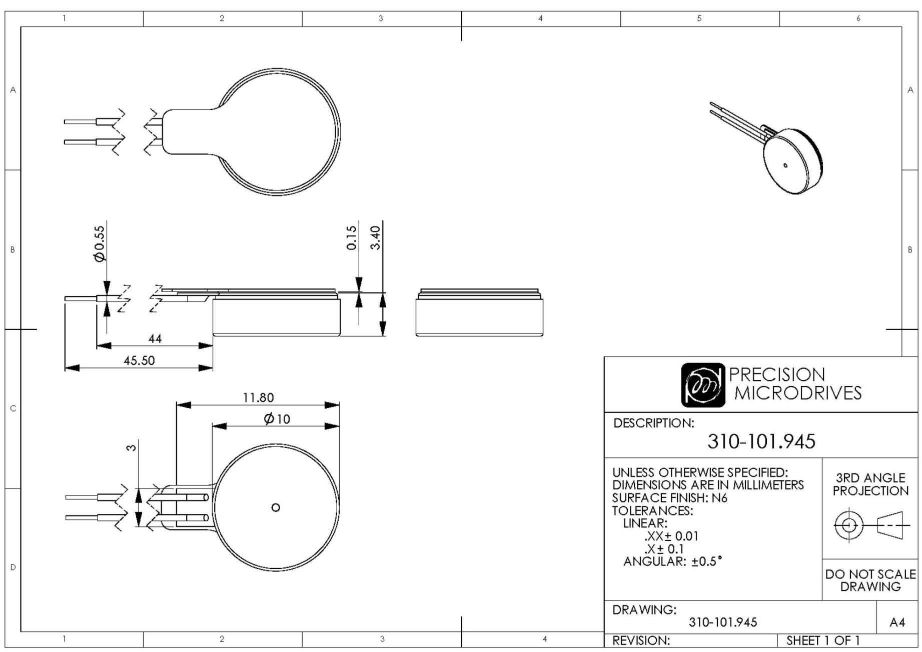
Tel: +44 (0) 1932 252482
Fax: +44 (0) 1932 325353
Email: sales@precisionmicrodrives.com



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